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ABSTRACT

This concept module on resistance is one of thirteen modules that provide a flexible, laboratory-based physics instructional package designed to meet the specialized needs of students in two-year, postsecondary technical schools. Each of the thirteen concept modules discusses a single physics concept and how it is applied to each energy system. This module discusses (1) the phenomenon referred to in a general way as resistance and (2) the application of the concept of resistance to mechanical, fluidal, electrical, and thermal systems. Included with the concept module are nineteen application modules that discuss a specific application of a single concept in a single energy system, and contain a student laboratory exercise. Laboratory modules included are Static and Sliding Friction; Effect of Lubricants; Rolling Friction; Laminar and Turbulent Flow; Viscosity; Fluid Resistance in Pipes; Valves and Regulators; Shock Absorbers; Drag-Resistance to Motion through Fluids; Ohm's Law; Series and Parallel Resistors; Internal Resistance of a Battery; Conductors, Semiconductors, and Insulators; Resistance of Wires; Resistance of Semiconductor Junctions; Resistance of Gas Laser Tubes; Volt-Ohm Milliammeter; Thermal Conductivity; and Heat Flow through Insulation. (LRA)

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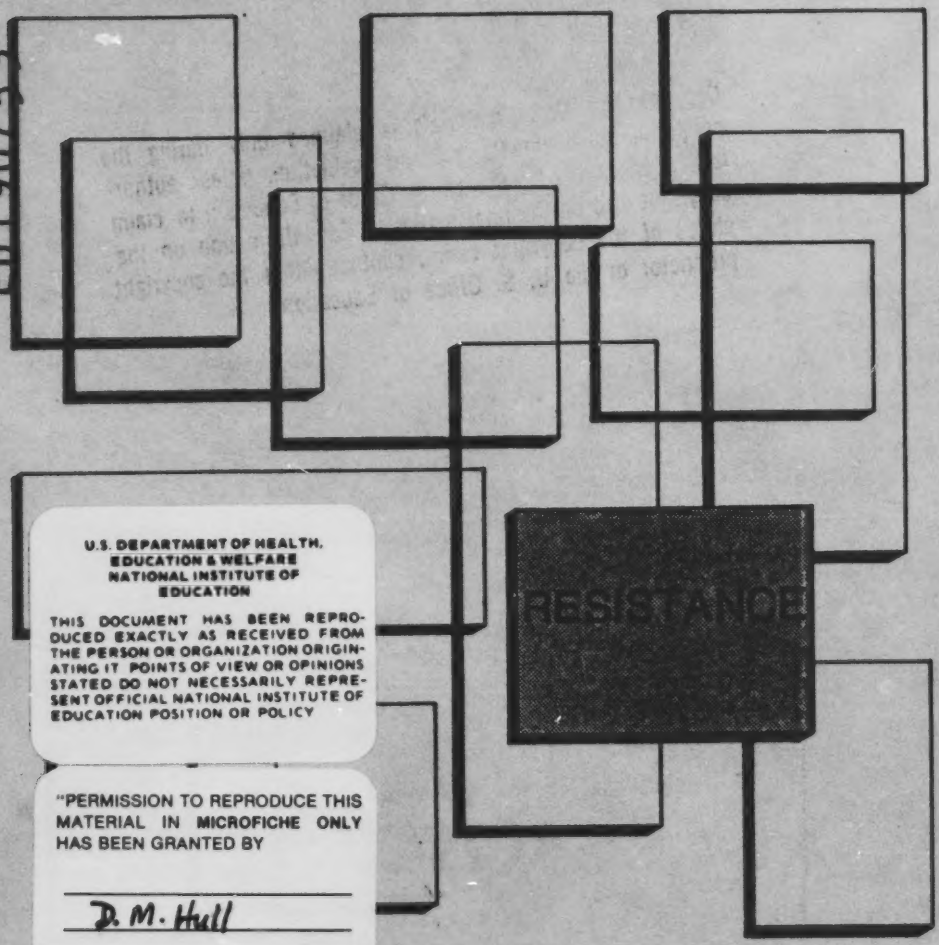
UNIFIED TECHNICAL CONCEPTS

CONCEPT MODULE 5-0

ED190753



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INTRODUCTION TO UTC

Complex, modern equipment often contains combinations of hydraulic, pneumatic, thermodynamic or optical subsystems, as well as mechanical and electrical components. These subsystems and components appear not in isolation but as interdependent parts of complex systems. Consequently, a modern technician must understand not only the separate subsystems but also their interrelationships and the roles they play in an integrated system.

Since physics provides the foundation for modern technology, physics instruction in technical programs cannot be overemphasized. Physics courses for technicians should achieve three major objectives:

- Provide students with all the basic physics principles that apply to their chosen field
- Reinforce these principles through the use of "real" examples and hands-on experience.
- Organize knowledge and skills gained in a manner that provides ease of application in solving systems-oriented problems.

These objectives must be accomplished in a minimum of instructional time, and in a manner flexible enough to meet the needs of a variety of technical specialties.

Unified Technical Concepts (UTC) is a flexible, laboratory-based physics instructional package designed to meet the specialized needs of students in two-year, post-secondary technical schools. UTC organizes technical physics into 13 basic concepts (Force, Work, etc.) that apply in four "energy systems" (Mechanical, Fluidal, Electrical, Thermal). Each of the 13 "concept" modules discusses a single physics concept and how it is applied to each energy system. Similarly, each "application" module discusses a specific application of a single concept in a single energy system, and contains a student laboratory exercise.

The recommended prerequisite for UTC is one year of high school algebra, but eight supplementary modules are available for students requiring additional skills or review in the areas of math, units and graphing.

UTC is an alternate method of presenting what heretofore has been a formidable and sometimes confusing subject for technicians. It provides laboratory experiments that apply to specific technological fields, which allows a student to relate more quickly to module content - to understand how it applies to a specific technology.

UTC also represents a unique approach to teaching applied physics. Its flexible modular format allows it to be tailored by physics and technology instructors to meet

specific needs of students in a specific technology.

STRUCTURE OF UTC

The modern world is based on the control and application of energy. Technology is the means by which that energy is applied to accomplish a desired task. Technical physics, being primarily a study of the physical basis of the control and use of energy, can be categorized according to the type of energy involved. Thus, in UTC, physics is divided first into four "energy systems" - Mechanical, Fluidal, Electrical and Thermal.

The same divisions are characteristic of traditional approaches to teaching technical physics. A student usually begins by studying mechanics. Once this branch of physics (energy system) is mastered, electromagnetism, thermodynamics and hydraulics are studied (one energy system at a time).

UTC takes a different approach.

CONCEPTS IN PHYSICS

The basic ideas, or "concepts," of physics appear in all energy systems, and these concepts relate to one another in similar ways in all systems. UTC unifies technical physics by presenting first the physics concept and then its application in each energy system.

The first concept studied, for example, is that of force, - the physical quantity that produces motion. The basic characteristics of force are followed by a discussion of how this concept applies to "forcelike quantities" in the following energy "systems":

- In mechanical systems <u>force</u> and <u>torque</u> cause motion of mass.
- In fluidal systems <u>pressure difference</u> causes motion of fluids.
- In electrical systems <u>potential difference</u> causes motion of mass.
- In thermal systems <u>temperature difference</u> causes motion of heat energy.

Problems, demonstrations and hands-on laboratory exercises are used to show the application of the concept in each energy system, and to specific devices or processes common in modern technology.

Thus, UTC provides a student with the basic concepts of physics reinforced by practical application and organized into a consistent whole; UTC is readily applied to future technical problems, whether in other courses or on the job.

COMPONENTS OF UTC

UTC incorporates three types of modules.

CONCEPT MODULES

Thirteen concept modules form the backbone of UTC (each presents a single concept in applied physics and discusses the application of that concept in each energy system):

1-0 Force.
2-0 Work.
3-0 Rate.
4-0 Momentum.
5-0 Resistance.
6-0 Power.
7-0 Potential and Kinetic Energy.
8-0 Force Transformers.
9-0 Energy Convertors.
10-0 Transducers.
11-0 Vibrations and Waves.
12-0 Time Constants.
13-0 Radiation.

APPLICATION MODULES

Each of the 170 application modules discusses the application of a single physics concept in a single energy system, and each module includes a laboratory exercise in which students investigate the application. For example, 5E5 "Resistance of Wires" (located under Concept 5-0 "Resistance"), discusses the electrical resistance of wires. In the laboratory, students calculate and measure experimentally the resistance of various wires.

SUPPLEMENTARY MODULES

In UTC, mathematics has been reduced to a minimum: one year of high school algebra is adequate preparation. The following eight supplementary modules are available for students requiring additional preparation or review:

S1 Formula Interpretation.
S2 International System of Units.
S3 Logarithms and Exponents.
S4 Angles and Triangles.
S5 Vectors and Scalars.
S6 Dimensional Analysis.
S7 Reading and Drawing Graphs.
S8 Precision, Accuracy, and Measurement.

STRUCTURE OF A UTC MODULE

Each module in UTC contains seven basic elements:

INTRODUCTION

A brief description of the topics to be discussed, and their importance in technology, introduces each module.

PREREQUISITES

A list of prerequisite UTC modules, and notice of any special knowledge or skills required for successful completion of the module, are given.

OBJECTIVES

Specific tasks that a student should be able to accomplish after completing the module are stated in behavioral terms; objectives also are the basis of testing for UTC.

DISCUSSION

This segment is an explanation of the topic to be studied. It contains the appropriate physics as well as examples of its application. The discussion includes development of equations, example problems, figures and tables of useful data. It addresses each of the objectives (except those pertaining directly to a laboratory experiment).

LABORATORY (called DEMONSTRATIONS in the Concept Modules)

The laboratory section of UTC modules consists of the following three parts:

- "Materials." A list of all equipment and supplies required for the laboratory.
- "Procedure." A step-by-step set of instructions for performing the experiment.
- "Data." An organized format for recording all necessary data and observations.

SELF CHECK

A set of questions and problems based on the module objectives is included. It is intended for use by students to check their own understanding of module content.

REFERENCES

This list of sources directs students to additional information on topics discussed in the module.

TABLE OF CONTENTS

5-0	Resistance
5M1	Static and Sliding Friction
5M2	Effect of Lubricants
5M3	Rolling Friction
5F1	Laminar and Turbulent Flow
5F2	Viscosity
5F3	Fluid Resistance in Pipes
5F4	Valves and Regulators
5F5	Shock Absorbers
5F6	Drag, Resistance to Motion Through Fluids
5E1	Ohm's Law
5E2	Series and Parallel Resistors
5E3	Internal Resistance of a Battery
5E4	Conductors, Semiconductors, and Insulators
5E5	Resistance of Wires
5E6	Resistance of Semiconductor Junctions
5E7	Resistance of Gas Laser Tubes
5E8	Volt-Ohm-Milliammeter
5T1	Thermal Conductivity
5T2	Heat Flow Through Insulation

INTRODUCTION

Motion of a moving system gradually dies out unless a force-like quantity is present to maintain it. A small child in a swing must be pushed continually to be kept moving; otherwise, oscillations of the swing grow smaller and smaller, until all motion ceases. A phonograph turntable will slow down and stop when its electrical power is turned off. A little reflection will convince one that when a moving system is not assisted by some forcelike quantity, the motion gradually decreases until it stops.

Some systems maintain motion without assistance for a longer time than others; but in all cases, motion ultimately ceases if no forcelike quantities are present to maintain it. This dying out of motion is the result of resistance within the system. Resistance appears in different forms in different energy systems, but in all cases creates forcelike quantities that oppose motion within the system.

This module discusses (1) the phenomenon referred to in a general way as "resistance" and (2) the application of the concept of resistance to mechanical, fluidal, electrical, and thermal systems. The discussion includes the similarities of resistance in all energy systems. These similarities make resistance a unifying concept. The discussion also includes the differences in resistance characteristics from one system to another.

PREREQUISITES

The student should have completed Concept Module 3-0, "Rate."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Define resistance in a general way and state the final form of the energy expended when a forcelike quantity does work to overcome resistance in any energy system.
- Calculate the magnitudes of starting and sliding frictional forces, given the mass or weight of the object, the coefficients of friction, and the angle of incline.

- Given two of the following quantities in fluidal, electrical, and thermal systems, determine the third:

  Forcelike quantity.
  Rate.
  Resistance.

- Describe the differences in laminar and turbulent flow.

- State the factors contributing to fluid resistance in pipes.

- State the factors contributing to electrical resistance in wires.

- State the factors contributing to the thermal resistance of objects.

- Describe with the use of graphs the definition of resistance as the ratio of forcelike quantity to rate in fluidal, electrical, and thermal systems. Include the units of forcelike quantity, rate, and resistance for each system.

- State the fundamental difference between sliding friction and resistance as it applies to fluidal, electrical, and thermal systems.

DISCUSSION

Resistance is an opposition to motion. It acts to oppose the forcelike quantities in all energy systems, thus causing a reduction of rates. If no forcelike quantities are present to counteract the affects of resistance, motion in the system will die out gradually and eventually will cease altogether. Although some systems maintain motion without assistance for a longer time than others, motion ultimately ceases in all instances.

If a moving system is to be maintained in motion at a constant rate, a forcelike quantity must act continuously upon the system and, in acting upon a moving system, must do work. The work done against friction in all energy systems is converted to heat energy. This process is taken advantage of in systems in which the conversion of other forms of energy to heat energy is desirable. In other cases, the energy converted to heat is wasted and cannot be recovered. Often, this heat energy causes thermal problems in a system, and steps must be taken to remove it. A stream of water used to cool the edge of a glass-cutting wheel is an example.

The following are examples of the affects of resistance in the four energy systems discussed in this module:

- In mechanical systems, resistance appears as friction between any two surfaces in contact. The affect of friction is to slow the motion of moving objects and to prevent the motion of stationary objects. Lubricants are used to reduce frictional forces and, thus, to reduce the force necessary to maintain motion and the amount of energy converted to heat.

- In fluidal systems, resistance appears as drag (fluid friction) forces on solid objects moving through fluids and as fluid resistance that limits fluid-flow rates through pipes. Much of the energy used by an automobile appears as work done against the fluid friction of the air.

- In electrical systems, electrical resistance opposes current in conductors. In electrical power distribution systems, this resistance must be minimized to reduce energy losses. In heating devices, such as toasters and electric heaters, resistance is employed to convert electrical energy into heat energy.

- In thermal systems, resistance appears as the opposition to heat flow. Materials, such as metals, that transmit heat readily have low thermal resistance. Thermal insulators are materials having high resistances to heat flow. In this system, resistance acts to reduce the rate of motion only. There is no energy available to be converted into heat, since only heat energy is present in thermal systems.

All these points bring to mind a fascinating question, not of vital concern at this stage of study; but just pause for a moment to ask it. "Is a completely frictionless system possible?" If such a system could be developed or found, no energy waste would occur due to resistance affects; in other words, the system would be 100% efficient. In fact, sometimes such an ideal situation can be approached very closely. For example, a rocket ship moving through the near-vacuum of outer space encounters very little resistance to its motion and coasts for great distances without additional energy input. In electrical systems, an electrical current can be maintained for a very long time without additional energy input in the "resistanceless" circuit made of a superconductor. The fact remains, however, that a perfectly frictionless system is an ideal.

In summary, a moving system involves some degree of resistance to motion. To maintain motion, additional energy input to the system is required. Where the heat produced by this additional energy is not desirable, it represents a waste of energy; and an effort is made to reduce resistance of the system. There are cases, however, when the heat produced is taken advantage of and put to some useful purpose, as for example, with industrial heat exchangers.

The remainder of this module discusses in greater detail the types of resistance introduced above.

MECHANICAL SYSTEMS - DRY FRICTION

Bodies in contact, and in relative motion with respect to one another — that is, rubbing against each other — produce a resistance to the motion, usually called "dry friction." This term is applied to distinguish this type of friction from the friction that a body experiences as it moves through a fluid. Such fluid friction often is called "viscosity," which will be considered later.

A simple and effective way for the student to understand this discussion is to think of a block of wood being dragged along the top surface of a table. A string is tied to the side of the block, and the block is being pulled in a horizontal direction (Figure 1). If a spring scale is introduced between the hand and the string, the scale will register the force required to drag the block along the table. The force that must be applied to do nothing more than slide the block along at constant speed is a measure of the frictional force resisting the motion. This frictional force originates at the point where the block surface and table surface are in actual contact. Microscopic inspection of this region shows that the surfaces are far

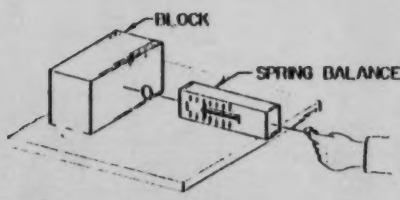


FIG. 1

from smooth: both surfaces have small and irregular "bumps." When stationary, many of the small bumps, or protrusions, of the block surface "lock" into corresponding holes in the table surface, and vice versa (Figure 2).

A certain amount of force is required to overcome the physical barriers (resistance) to motion provided by these tiny irregularities. Even surfaces that appear to be very smooth are, in fact, irregular. No surface can be perfectly smooth, because matter is ultimately granular in nature. At any rate, the smoother the surfaces, the less the frictional drag.

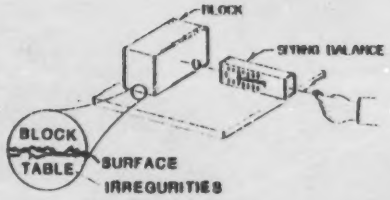


FIG. 2

Dry friction, therefore, depends upon the types of surfaces involved. Wood dragged along a smooth tile floor involves less friction than wood dragged against a wooden floor, and so on. How the lubrication of surfaces reduces frictional force should be obvious now. If the table top is covered with a film of liquid or oil, for example, the film can act to hold the block and table surfaces apart enough to reduce collisions of their irregular surface bumps (Figure 3).

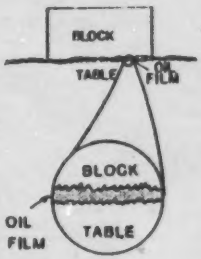
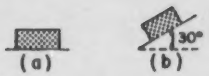


FIG. 3

Apart from the types of surfaces involved, what other factors might influence frictional force? Obviously, weight (W) of the block makes a difference. A heavy crate is more difficult to drag than a light crate of the same size and shape. More precisely, the frictional force really depends upon the force pushing the two surfaces together. This force usually is called the "normal force" (N), because its direction is perpendicular, or "normal," to the surface area. This bit of precision is important, because weight W and normal force N are not always identical. Example A shows cases in which weight and normal force are the same and in which they are different. Example A also shows the importance of treating forces as vectors and of being able to resolve such vectors into components.

EXAMPLE A: NORMAL FORCE PROBLEM	
Given:	Two crates weigh 100 pounds each. One rests on a horizontal surface and the other on a surface 30° from horizontal.
Find:	The normal force on each crate.
Solution:	(a) In this case, weight of the crate acts perpendicularly to the horizontal floor. Thus, weight and normal force are identical. W = 100 pounds. N = 100 pounds.

(b) In this case, weight continues to act vertically downward. Its component perpendicular to the surface is less than the weight and can be found from the vector triangle.



$N = W \cos 30°$

$= (100)(\cos 30°)$

$= (100)(0.866)$

$N = 86.6$ pounds

What factors other than the types of surfaces and the normal force pressing them together are involved in determining the frictional force? Surprisingly, nothing else matters much. For example, consider whether or not the amount of surface area itself makes a significant difference. Consider a crate being dragged along the floor, first on its large side and then on its small side (Figure 4). One side (a) has a large surface area, the other (b) a small surface area in contact with the floor. Of course, weight of the crate does not change. There is no significant difference in the frictional forces acting. This may seem rather remarkable at first, because our understanding of the source of friction would lead us to believe that the larger surface area in contact with the floor would have more friction. There are more surface irregularities to become locked together. But, what we have overlooked is that, in this case, there is less weight directly above the irregularities pressing them into the floor. Apparently, these two affects cancel each other. Thus, dry friction is independent of the contact surface area.

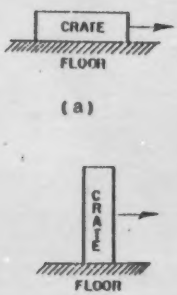


FIG. 4

Consider whether the speed with which the block is dragged along makes a difference. Again, an experiment would show that speed is not important — unless speeds are reached at which air friction is no longer negligible. Therefore, dry friction is independent of velocity.

The conclusion can be made that dry-frictional forces depend upon two factors:

(1) Nature of the sliding surfaces.
(2) Normal force pressing them together.

Further experiments show that, in fact, frictional force is directly proportional to the normal force; that is, if the normal force is doubled, frictional force also is doubled. All this information is summarized in Equation 1.

$$f = \mu N \qquad (1)$$

where

f = frictional force.
N = normal force.
μ = "coefficient of friction."

The coefficient of friction μ depends upon the nature of the two surfaces involved. It is a pure number without units, being simply the ratio of two forces, f/N. Some approximate values for the coefficient of friction for common materials are given in Table 1. Example B illustrates the usefulness of Equation 1.

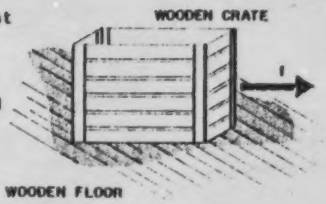
TABLE 1: COEFFICIENTS OF SLIDING FRICTION (μ)

Coefficients of Sliding Friction (μ) (Values are approximate.)	
Wood on wood	0.3
Wood on stone	0.4
Metal on metal	0.15
Metal on wood	0.5
Leather on wood	0.4
Rubber on dry concrete	0.7
Rubber on wet concrete	0.5

EXAMPLE B: DRY SLIDING FRICTION

Given: The 100-pound crate of Example A has a coefficient of friction between crate and floor of 0.25.

Find: What force must be applied to overcome friction and to keep the crate sliding at constant speed in each case, a and b.



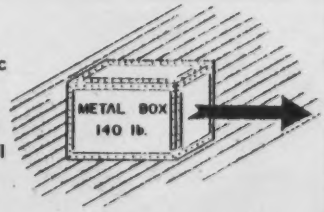
Solution: (a) $N = 100$ pounds, $\mu = 0.25$
$f = \mu N = (0.25)(100) = 25.0$ pounds

(b) $N = 86.6$ pounds, $\mu = 0.25$
$f = \mu N = (0.25)(86.6) = 21.65$ pounds

There is a small complication in this simple theory. A larger force is required to start a box sliding than to keep it sliding. In fact, more effort is required to unlock the two surfaces when they are stationary than to keep them sliding when motion has begun, which means that the differences between coefficients of "starting friction" and coefficients of "sliding friction" must be identified. The first is called a static friction coefficient μ_s and the second a kinetic friction coefficient μ_k. For the same two surfaces, μ_s will be slightly greater than μ_k. Consequences of the difference in μ_s and μ_k are illustrated in Example C.

EXAMPLE C: STATIC AND KINETIC DRY FRICTION

Given: A metal box weighing 140 pounds rests on a horizontal wooden floor. The coefficient of static friction for these surfaces is 0.55, and the coefficient of kinetic friction is 0.50. A pull rope is attached.



Find: What happens as pull on the rope is increased.

Solution: Static frictional force $f_s = \mu_s N = (0.55)(140)$
$= 77$ pounds

Kinetic frictional force $f_k = \mu_k N = (0.50)(140)$
$= 70$ pounds

Therefore, no motion of the box occurs until pull on the rope reaches 77 lbs. At this point, the box begins to slide. Since pull required to keep the box sliding is only 70 lbs, the box will begin to increase in speed, or accelerate, unless the pull is reduced to 70 lbs. If the pull is reduced below 70 lbs, however, the box gradually will come to a stop.

Still another type of friction occurs when one object is rolling along the surface of another. The same general equation can be used, but proper value of the coefficient of "rolling friction" to be used must be determined.

Sliding friction, remember, is not dependent upon the velocity of the surfaces involved. Figure 5 is a graph of frictional force versus velocity. Static friction is the maximum possible value of frictional force that can exist between stationary surfaces for a given normal force. If a force applied parallel to the surface exceeds the magnitude of the static friction, motion results. Once motion has begun, the frictional force drops to the sliding friction value and remains there as long as the surfaces are in motion. Sliding friction and rolling friction are the only types of resistance that do not change as rate changes.

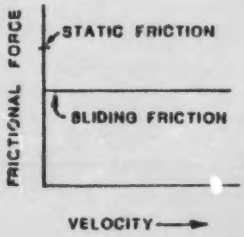


FIG. 5

FLUIDAL SYSTEMS

Friction or resistive forces also occur in fluids (liquids or gases). We distinguish two cases: (1) a solid body moving through a fluid and (2) the internal friction, or friction of a fluid with itself, usually described as the "viscosity" of the fluid.

RESISTANCE TO MOTION OF A SOLID BODY THROUGH A FLUID - FLUID FRICTION

A solid body that forces its way through a fluid, like a ship is forced through the ocean, must do the work of separating the fluid to allow passage. Thus, the moving object encounters resistive forces, or fluid friction, in its motion. A minimal amount of energy loss occurs when the water is simply separated and then comes together again after the passage, without the creation of eddies and other kinds of swirling motion of the fluid. The simpler motion of the fluid is accomplished by the streamlining of the shape of the object. Unlike the case of dry friction, the shape of the object now is all important. Much is learned about streamlining from the natural shapes of birds and of fish as they move effortlessly through air and water. Their shapes are compared with the present designs for automobiles and especially for jet airplanes. Turbulence (swirling) is more difficult to avoid at high velocities; therefore, streamlining is especially important in the design of vehicles that must move at relatively high speeds through air or water. In contrast, recall the cumbersome shapes of weather satellites. Although they move in orbit at tremendous speeds, they move through a near vacuum — that is, the total absence of air — so that streamlining is not important.

At higher speeds, more turbulence is created; therefore, more energy is dissipated because of fluid friction in heating the fluid. This additional energy is wasted. To operate an automobile running at high speeds costs much more than at low speeds, as evidenced by the poorer figure for miles per gallon of gasoline in operating an automobile against air friction at higher speeds. Or equivalently, recall the difference in effort required in walking through water and in running through it at the beach.

The sport of skydiving (Figure 6) illustrates the increase of fluid friction with velocity. A skydiver who falls a great distance before opening the parachute quickly reaches a steady velocity of fall — a "terminal velocity" of about 130 miles per hour. From the moment of jumping, the diver's speed increases because of weight (that is, the pull of the earth). At the same time, the velocity and the frictional force of air are increasing. When this upward force of air (drag) becomes equal to the downward force (caused by the diver's weight), these forces cancel each other; and the diver maintains a certain velocity. Before hitting the ground, pulling on the rip-cord releases the parachute. The parachute is anything but streamlined in shape, and it increases air drag to such an extent that the skydiver continues to fall at a much smaller terminal velocity of only a few feet per second.

FIG. 6

Unlike dry friction, fluid friction depends upon velocity of the motion of a body through the fluid. If the body is well streamlined and if fluid moves past the body without turbulence, the fluid flow is called "streamline," or "laminar" flow. In this case, frictional forces are very nearly proportional to the velocity; that is, frictional force doubles when the velocity doubles. As velocity is increased further, however, turbulence eventually will be encountered; and then the frictional forces will increase more rapidly with velocity. For example, air drag on an airplane wing is proportional to the square of the velocity: frictional forces become four times as great when the speed doubles. At even higher speeds, the forces may vary as the cube or higher powers of the velocity. Velocity is an important factor, therefore, in the determination of fluid friction, but the exact equation depends very much upon conditions, and must be determined experimentally.

Fluid friction presents a way of thinking about the resistance of a system that it will be valid in other systems as well. The following paragraphs present an experiment and a graphical analysis of the results. The relationships examined will be applied to other energy systems later in this module. Although these experiments can be done in principle, some of the measurements would be difficult to make because of the choice of materials tested. The materials will be ignored, since the principles are more important.

Imagine taking data and plotting it in the following simple experiment, with the objective of determining the frictional force on a solid body moving through a specified liquid. A cylinder (Figure 7) is filled with a fluid, water. A metal sphere suspended on a string is raised at constant speed, encountering fluid frictional drag. The spring scale registers pull of the string P upward on the sphere. Pulling downward on the sphere are its weight W and the frictional drag f. When weight and measured force P are known, the frictional drag can be determined from $f = P - W$. (To be more exact, a buoyant force P also forces the sphere upward.) The buoyant force would equal the weight of the fluid that the small sphere displaces. Data is taken in this way for values of f corresponding to different velocities of rise v. The plotting of all these points gives a graph that looks something like that shown in Figure 8. Each point represents a corresponding pair of values of v and f. The set of points appears to determine a straight line drawn through the points.

FIG. 7

Next, imagine that the experiment is repeated, but that the cylinder is filled with molasses, and then with alcohol. If all these graphs are plotted together, something like Figure 9 would result. Each straight line has a different inclination, or slope, the significance of which will be investigated.

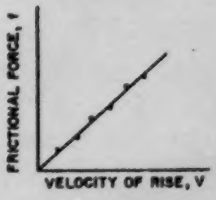


FIG. 8

At a given velocity of rise, like v_1, the graph shows that molasses presents the greatest frictional force, water the next largest, and alcohol the least. These values are shown on the graphs as f_m, f_w, and f_a, respectively. Therefore, the line with the greatest slope indicates a fluid that offers greater fluid friction. A quick glance at the curves then shows that molasses is more viscous than water and water more viscous than alcohol (as might be expected); therefore, when forces are plotted against velocities in this way, slopes of the graphs are a measure of resistance of the system. If velocities used in this experiment were large enough to create turbulence, the graphs would be curved rather than straight. When force is proportional to velocity, the graph is a striaght line; when force becomes proportional to the second or third powers of velocity, the curves deviate from straight lines.

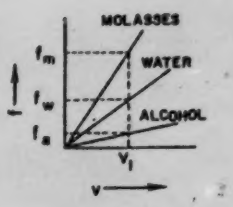


FIG. 9

FLUID RESISTANCE IN PIPES

When a fluid is flowing through a pipe, certain parts of the fluid are moving faster than other parts, so that internal fluid friction is involved. Fluids with high internal friction, like molasses, have a high viscosity; those like alcohol or gases have a much smaller viscosity. As with coefficients of dry friction, viscosity can be defined more precisely and measured, enabling introduction of a useful number called the "coefficient of viscosity."

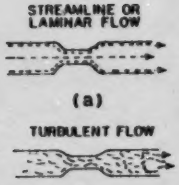


FIG. 10

Energy losses due to the viscosity of fluids become important when fluids must be transported over great distances. Consider pipelines that carry petroleum, natural gas, and water across large sections of the country. The Alaskan pipeline is an excellent example. Energy losses due to fluid friction must be compensated for by extra pumps at regular intervals along the pipelines to maintain necessary pressure. The energy required to operate these pumps is essentially the energy lost by the fluid due to viscosity. These energy losses are greatest when flow is turbulent. Figure 10 shows a section of pipeline that includes a constriction. The dotted lines in Figure 10a indicate paths of fluid particles in the case of streamline or laminar flow, and then in the case of turbulent flow (10b). The portions of the fluid near the inner pipe wall move more slowly than the fluid near the center of the pipe, meaning that between different portions of the fluid there is relative motion, which gives rise to fluid friction. In streamline flow, these portions, or layers, of fluid simply slide past one another. In turbulent flow, complex motions that waste energy occur.

For occasions when fluid flow is without turbulence (streamline), the average resistance to fluid flow can be calculated with Equation 2.

$$R_F = \frac{\Delta p}{Q_H} \qquad (2)$$

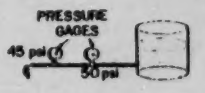
where

R_F = fluid resistance.
Δp = pressure difference across pipe.
Q_H = volume flow rate; velocity.

The resulting units for resistance will be pressure units (N/m^2 or lb/in^2) divided by flow rate units (gal/min or m^3/s). The use of this equation is illustrated in Example D.

EXAMPLE D: FLUID FLOW PROBLEM

Given: A pipe has an inlet pressure of 50 psi and an outlet pressure of 45 psi. Fluid is flowing in the pipe at the rate of 25 gal/min.



Find: Internal resistance of the pipe.

Solution:

$$R_F = \frac{\Delta p}{Q_H}$$

$$= \frac{50\ lb/in^2 - 45\ lb/in^2}{25\ gal/min}$$

$$= \frac{5 \text{ lb/in}^2}{25 \text{ gal/min}}$$

$$R_F = 0.2 \frac{\text{lb/in}^2}{\text{gal/min}}$$

This answer means that the resistance of the pipe is 0.2 lb/in^2 for every gal/min velocity.

When fluid flows through a pipe, there is a frictional drag between it and the inner wall of the pipe and a viscous drag between successive layers of fluid from the wall inwards to the center, where flow velocity is greatest. To maintain the flow, pressure (forcelike quantity in the fluid system) on the input end must be greater than pressure on the output end.

Suppose our pipe is just a glass tube at the base of a cylinder of water (Figure 11). The pressure differential across the pipe, $p_1 - p_2$, is then just due to the head of water in the cylinder, and is recorded simply in units of inches of water head. If the valve at the end of the pipe is opened for a measured time interval and the outflow of water is collected and measured, volume rate of the flow in milliliters per minute or gallons per hour is determined. If collecting time is short enough, the reservoir level will not drop much, and the water is assumed to be collected at a constant pressure differential. Data taken in this way is plotted as pressure differential (forcelike quantity) against flow rate. Measurement of a different flow rate for each different height of water (for three different pipes of different diameter) will result in three separate graphs as before (Figure 12).

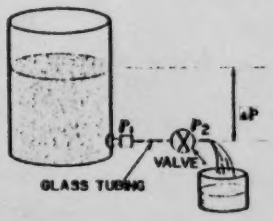


FIG. 11

The pipe represented by the line of greatest slope is the one that offers the greatest resistance. For a given flow rate, pipe No. 1 evidently requires the greatest pressure differential to overcome its own resistance to fluid flow. As before, when forcelike quantity is plotted against ratelike quantity, a graph is arrived at in which the slope is a measure of resistance offered by the system.

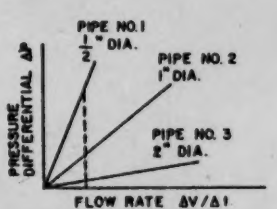


FIG. 12

The value of fluid resistance in a long, straight, smooth pipe depends upon the following three factors:

- Length of the pipe. Fluid resistance increases linearly with pipe length. If the length is doubled, the resistance doubles.

- Area of the pipe. The area of the pipe increases as the square of the diameter, and fluid resistance decreases as the square of the area. Thus, doubling of the pipe diameter increases the area by a factor of 4 (2^2) and decreases the resistance by a factor of 16 (4^2).

- Viscosity of the fluid. Fluid resistance increases with an increase in viscosity.

Roughness of the pipe inner walls, bend, and constrictions also add to fluid resistance.

ELECTRICAL SYSTEMS

An electric current in a wire is an orderly motion of electrons in the wire. For direct current, this motion is a steady progress of electrons from one end to the other. For alternating current, there is an orderly motion of electrons back and forth at the frequency (usually 60 cycles per second) of the electrical system. Of course, these electrons undergo collisions and random motions in the process. But when a current exists, the electrons experience a net drift through the material. In contrast, when no current exists in the wire, motion of the electrons is random; and the average effect upon their motions is simply no motion at all.

Because these electrons are "free" to wander through the bulk of the material without being captured by any one atom in particular, they contribute to both heat and electrical conduction. Good conductors of heat (metals) usually make good electrical conductors, and vice versa. Materials differ widely in their ability to conduct electricity — from copper, near the good-conductor end of the spectrum, to hard rubber, near the good-insulator end. Even liquids (salt water, for example) make rather good electrical conductors. In this case, individual electrons do not carry the current, but charged atoms or ions that do the job.

An experiment is now described that will enable electrical resistance to be presented in a manner analogous to the fluid resistance in pipes previously discussed. In Module 1-0, force-like quantity in the electrical system that produces charge transport, or electrical current, is described as a potential difference V, in volts. The rate-like quantity is the rate at which charge is transferred through the material, which is precisely what is meant by electrical current. The most common unit of current is the number of coulombs of charge per second, which are called amperes of current.

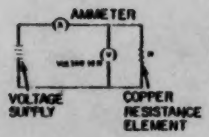


FIG. 13

Consider a copper element (a piece of copper of a particular size and shape) included in an electrical circuit (Figure 13) made up of a variable voltage source and two measuring instruments — a voltmeter to measure potential difference across the copper

element, and an ammeter to measure charge flow rate or current through the element. Symbols used for a battery and for a resistor R represent the copper element.

Simply vary the potential difference V and read the corresponding value of current I off the ammeter. If this data is plotted as shown, a straight-line graph results for copper.

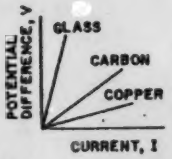


FIG. 14

Data is taken for a sample of glass and for a sample of carbon, both cut to the same size and shape as the copper, so as to compare the results easily. By now, these results should be meaningful. Plotted in Figure 14 is the forcelike quantity V against the ratelike quantity I. The slope of these lines is again a measure of the resistance. Evidently, glass has more resistance to electrical conduction than does carbon. Copper turns out to be the best conductor of the three, as might be suspected.

The slope of these straight lines is found, as usual, by taking the interval ΔV between any two points on the line and dividing by the corresponding interval ΔI. One point of the interval is chosen as the origin, shown in Figure 15; then, slope = V/I. As discussed previously, the slope is a measure of resistance of the system. Here electrical resistance R is defined as the ratio of V/I, as in Equation 3.

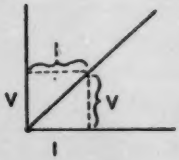


FIG. 15

$$R = \frac{V}{I} \qquad (3)$$

where

R = resistance.
V = voltage.
I = current.

If V is in volts and I is in amperes, R is defined in terms of a unit called the "ohm." One ohm of resistance is the resistance of an element in which one ampere of current results when one volt of potential difference exists across it. Briefly, an ohm is one volt per ampere. The name "Ohm" was chosen in honor of the discoverer of this basic law, the German scientist Georg Simon Ohm. This law is referred to as "Ohm's law." Examples E and F illustrate use of Ohm's law to calculate resistance and current in electrical circuits.

EXAMPLE E: OHM'S LAW	
Given:	The circuit described above, with a current of 2 amperes when the voltage is 10 volts.
Find:	Resistance of the resistive element.

Solution:	The voltage, current, and resistance are related simply through Ohm's law, V = IR or, R = V/I = (10 volts)/(2 amps) = 5 ohms

EXAMPLE F: OHM'S LAW	
Given:	Voltage is reduced to 4 volts.
Find:	Current through the same resistor.
Solution:	Ohm's law is applied again. This time, current is the unknown, so the law solving for I is used thusly: I = V/R = (4 volts)/(5 ohms) = 0.8 amps

The resistance of electrical conductors depends upon these three quantities:

- Length. The resistance of a wire increases linearly with its length. If length is doubled, resistance doubles.
- Area. Resistance decreases proportionally to the area of the conductor. If the area is doubled, resistance is reduced by one-half. If the diameter is doubled, the area increases by a factor of 4 and reduces the resistance to one-fourth the initial value.
- Resistivity of the conductor. Resistivity is a characteristic of the material from which the conductor is constructed. Copper has a low resistivity, and glass has a high resistivity. Resistance increases as resistivity is increased.

THERMAL SYSTEMS

Resistance in a thermal system can be understood in an analogous way. In many ways, the flow of heat energy through a bar is like the flow of fluid through a pipe or of change through a wire. As explained earlier in Module 1-0, the forcelike quantity that causes the flow in this case is a temperature difference ΔT, and the ratelike quantity is the heat flow rate Q_H (for example, in calories per second). The experiment in this case is much like the fluid-flow experiment in the previous section.

In Figure 16, there is a copper bar that conducts heat from its left end, held at an elevated temperature, to its right end, held at a lower temperature. To begin with, the left end of the

bar is in thermal contact with a steam bath, and the right end is in thermal contact with an ice bath. The steam bath, ice bath, and copper bar are all well-insulated. At atomspheric pressure, a steam bath at one end, and an ice bath at the other end would amount to a temperature differential of 100 C°. Heat energy associated with greater atomic vibrations at the left end gradually is transferred to the right end, raising its temperature. After the bar is left in this condition for some time, it comes to equilibrium — "steady state" condition reached, in which the temperature at each point of the rod no longer is changing, from the hot end to the cold end. The rate at which heat energy is being conducted through the rod under these steady-state conditions is of interest. Ways of measuring this quantity will depend upon the ingenuity of the experimenter. For simplicity, assuming adequate insulation of all components, the amount of ice melted in a given amount of time is measured. Known is amount of heat required to melt each gram of ice (the "heat of fusion" of ice is 80 calories per gram); also known is how much heat has been transferred in the given time interval. Therefore, the heat flow rate Q_H can be calculated. All that is necessary now is to change temperature of the constant-temperature bath at the left (Figure 16a), giving a different value for ΔT, and then measure the corresponding quantity Q_H from the ice melted on the right end (Figure 16b). In this way, pairs of data points for ΔT and Q_H are collected and plotted for the copper bar.

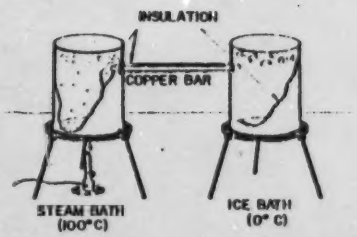


FIG. 16

If this process is repeated for other materials, such as a glass rod and a wooden rod, all the same length and cross section, a graph something like that shown in Figure 17 is produced. Interpretation proceeds as it did for the other systems. The fact that for a given flow rate, a larger temperature difference is needed for cork than for either glass or copper clearly means that cork offers the greatest resistance to heat flow. Of the three, copper offers the least resistance. Again, the slope of the lines is a measure of resistance offered by the thermal system. Of these three materials, cork is the best insulator, and copper is the best conductor.

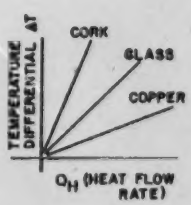


FIG. 17

Materials possessing a high resistance to heat flow are good insulators. Materials like cork, styrofoam, fiberglass, and even layers of air keep heat out (as in a refrigerator) or to keep heat in (as in homes). At other times, good conductors are desired to transfer heat. Metals make the best conductors, because they contain many free electrons that aid in transfer of heat energy.

Everyday items, such as metal radiators or the copper bottoms of tea kettles, are good examples.

Thermal resistance is defined by Equation 4.

$$R_T = \frac{\Delta T}{Q_H} \qquad (4)$$

where

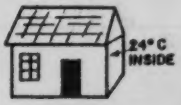
R_T = thermal resistance.
ΔT = temperature difference.
Q_H = heat flow rate.

The units of thermal resistance are temperature difference units (F° or C°) divided by heat flow rate units (Btu/hr or cal/g).

The use of this equation is illustrated in Example G.

EXAMPLE G: THERMAL RESISTANCE

Given: Temperature inside a house is 24°C; outside, the temperature is 4°C. A furnace supplies 2625 kcal to the room each hour to maintain the inside temperature of 24°C.



4°C OUTSIDE

Find: Thermal resistance of the house.

Solution:

$$R_T = \frac{T}{Q_H}$$

$$= \frac{24°C - 4°C}{2625 \text{ kcal/h}}$$

$$= \frac{20°C}{2625 \text{ kcal/h}}$$

$$R_T = 0.0076°C(\text{kcal/h})$$

This value tells us that the house gains 0.0076°C over the 4°C outside temperature for every kcal/h of heat flow from the furnace.

The thermal resistance of a sheet of material depends upon the following three quantities:

- Thickness. The resistance to heat flow increases linearly with thickness. The doubling of thickness doubles resistance.
- Area. The thermal resistance decreases linearly with increasing area. When area is doubled, resistance is halved.
- Thermal conductivity. If conductivity is increased (when materials are changed), resistance decreases.

SUMMARY

As shown previously, in different physical systems, an important phenomenon shows up as a resistance to motion with a corresponding energy loss, called the "characteristic" of the system resistance.

In the case of sliding friction, resistance is independent of velocity (rate). In fluidal, electrical, and thermal systems, the resistance can be analyzed and measured graphically by the plotting of (Figure 18) the forcelike quantity (y-axis) against the ratelike quantity (x-axis) for the particular system. Resistance of the system then is the slope of the curve. Usually, the curve is a straight line of constant slope passing through the origin. Then the slope can be written simply as the ratio of forcelike to ratelike quantities:

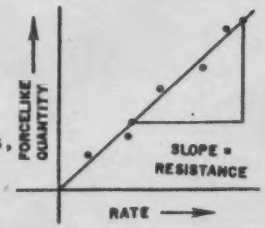
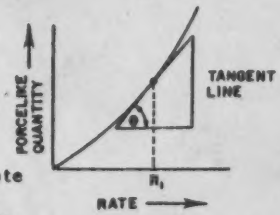


FIG. 18

$$\text{RESISTANCE} = \frac{\text{FORCELIKE QUANTITY}}{\text{RATE}}$$

There are times, however, when a graph of force versus rate will produce a curved graph. As indicated previously, in the case of turbulent fluid flow, this curve will occur because the frictional force then is proportional to higher powers of the velocity. The slope of the "line" will have different values at different points, which indicates that the resistance of the system is not a constant, but is changing continually. Resistance of the system can be found for any rate if the slope of the curve at the corresponding point (Figure 19) is found. Since the slope of a curve at a point on the curve is simply the slope of the tangent line to the curve at the point, resistance always can be found.



RESISTANCE OF SYSTEM WHEN OPERATING AT RATE R_1 IS THE SLOPE OF THE TANGENT LINE SHOWN.

FIG. 19

Table 2 contains a summary of the resistance in those systems in which resistance is dependent upon rate.

TABLE 2: RATE-DEPENDENT RESISTANCE			
SYSTEM	FORCELIKE QUANTITY	RATE	RESISTANCE
Fluidal	Pressure difference Δp	Volume flow rate Q_V	$R_F = \frac{\Delta p}{Q_V}$
Electrical	Voltage ΔV	Current I	$R_E = \frac{\Delta V}{I}$
Thermal	Temperature difference ΔT	Heat flow rate Q_H	$R_T = \frac{\Delta T}{Q_H}$

DRY FRICTION

MATERIALS

Wooden block with hook and table top with smooth surface.
String.
Calibrated spring balance.
Set of weights (up to kilogram in size).

PROCEDURE

When a block is sliding at a constant speed, it is in equilibrium, and the forces on it must balance. Therefore, the pulling force exerted on the block to move it must be exactly balanced by the frictional force holding it back. On a horizontal surface, the normal force is the same as the weight of the block. From such a simple experiment, the coefficient of sliding friction between block and table can be determined.

1. Weigh wooden block; record this value in Data Table 1 as N.

2. Connect a string and spring balance to block as shown (Figure 20); slide block along table top at a uniform speed slow enough so that spring balance can be read. Spring balance registers frictional drag on block. Record this value as f.

3. Repeat this process several times, each time adding more weight to top of block.

4. Plot normal force N (x-axis) against frictional force f (y-axis), using data from table; draw a smooth line through these points.

5. Measure slope of line to determine coefficient of sliding friction between block and table top.

6. Use the following equation to calculate μ_k for each trial: $\mu_k = f_k/N$. Average results. How does the average value compare with answer to step 5?

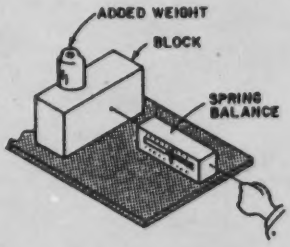


FIG. 20

DATA TABLE 1		
Sliding System	N (Total Weight Moved)	F (Spring Balance Reading)
Block alone		
Block with first weight added		
Block with second weight added		
Block with third weight added		
etc.		

FRICTION OF A BODY MOVING IN A FLUID

MATERIALS

Ball bearings approximately 6 mm diameter.
3 glass tubes at least 1 meter long and approximately 15 mm diameter.
Rubber stoppers for one end of each tube.
Motor oil and gear oil — 10w, 30w, and 90w.
Meter stick.
Stopwatch or other timer.
Vernier or micrometer calipers (metric units).

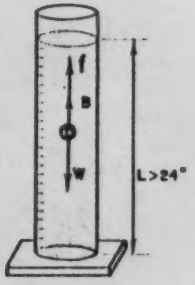


FIG. 21

PROCEDURE

An object falling freely in a fluid (Figure 21) reaches a terminal velocity, at which time it is in equilibrium. Upward forces balance the downward force. Downward force is the weight; upward forces are the buoyant force and the frictional drag of the fluid. This method will be used to measure frictional drag on a falling sphere for several different fluids.

1. Measure (in cm) ball bearing diameter with micrometer or vernier calipers. On a scale balance, determine their mass in grams. From this information, calculate volume ($V = 4/3\ \pi r^3$, where r is radius) and weight ($W = mg$) of bearing in cm^3 and dynes, respectively. Record all these results in Data Table 2.

2. Fill each cylinder with a different weight of oil (10w, 30w, and 90w); gently release ball bearing at surface for each different cylinder of oil; note how soon it reaches a terminal velocity. Make two marks on cylinder, as far apart as possible but within terminal velocity region of descent. Make a careful measurement of distance ℓ (in cm) between these marks with a meter stick.

3. Release ball bearing as before; time descent with a stopwatch, from first to second mark. Call this time t (seconds). Make at least three separate trials to measure t. Record these times with their average in Data Table 3.

4. Repeat for other two weights of oil supplied. Complete Data Table 3, calculating terminal velocity of descent for given ball bearing for each oil weight.

5. From given weight density (dynes per cm^3) of fluids used, calculate buoyant force on ball bearing in dynes for each fluid. Remember that —

   buoyant force = weight of displaced fluid
   = volume of ball bearing (cm^3) x weight density of fluid.

   Record in Data Table 4.

6. Calculate frictional force on ball bearing as it descends at terminal velocity in each weight of oil. Use fact that, in this case, forces are balanced so that: $f + B = W$, or $f = W - B$. Record in Data Table 4.

7. Determine resistance to motion offered by each oil. This resistance R will be ratio of frictional force f to terminal velocity of descent, v. $R = f/v$. Be sure to include proper units in results.

DATA TABLE 2
r (radius of ball bearing) = _____ cm
V (volume of ball bearing) = (4/3) r = _____ cm^3
m (mass of ball bearing) = _____ grams
W (weight of ball bearing) = mass (m) x acceleration of gravity (g)
= _____ grams x 980 cm/s^2
= _____ dynes

DATA TABLE 3					
ℓ = _____ cm.					
			time (s)	average time (s)	velocity ($v = \ell/t_{av}$) (cm/s)
Fluid 1 10w	Trial 1				
	Trial 2				
	Trial 3				
Trial 2 30w	Trial 1				
	Trial 2				
	Trial 3				
Trial 3 90w	Trial 1				
	Trial 2				
	Trial 3				

DATA TABLE 4				
	Weight Density of Fluid (d)	Buoyant Force (b=Vd)	Frictional Force (f=W-B)	Resistance (R = f/v)
Fluid 1 (10w oil)				
Fluid 2 (30w oil)				
Fluid 3 (90w oil)				

FLOW RESISTANCE OF A PIPE

MATERIALS

Large water tank (at least 5 gallon) with outlet near base.
Assorted glass tubing (with different bores and lengths) and matching bore rubber tubing.
Balance scale.
500-ml graduate.
Clamp for rubber tubing.

PROCEDURE

Resistance of a simple pipe to flow of water can be determined by measuring the rate of volume output for a given pressure differential.

1. Refer to Figure 22. Connect length of glass tubing to bottom outlet of water reservoir, using a short piece of rubber tubing. Place a clamp on rubber tube to stop water flow. Record length and bore diameter for glass tubing in Data Table 5.

2. Nearly fill reservoir, and measure water head h. Distance h measured in convenient length units represents pressure differential across tubing. Note: End of glass tube must be same height as outlet from reservoir.

3. With tubing in a horizontal position, open clamp to allow water to flow; catch outflow in a volume-calibrated container, such as a graduate. Time collection of this water with a stopwatch. Do not collect so much water that water head changes appreciably.

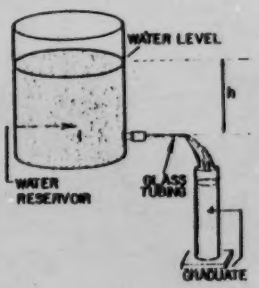


FIG. 22

4. Repeat for several (four or five) smaller values of pressure head h.

5. Repeat preceding steps for a second glass tube of different length and/or diameter bore.

6. From data taken, calculate volume flow rate Q_V; record in Data Table 5.

7. Plot on same graph sheet the data for tubing No. 1 first and then for tubing No. 2. Add pressure values (h) on vertical axis and volume flow rate on horizontal axis.

8. Determine slope of graph line for each tubing; record each value in proper units as resistance of tubing to fluid flow.

9. How are tubing dimensions related to its resistance?

DATA TABLE 5				
	h	V	t	Q_V
First piece of tubing Length				
Diameter of bore				
Resistance from graph				
Second piece of tubing Length				
Diameter of bore				
Resistance from graph				

ELECTRICAL RESISTANCE

MATERIALS

d.c. low-voltage power supply.
Milliammeter, d.c. (500-ma range).
Voltmeter, d.c. (15-volt range).
Three 1/4-watt resistors, between 100 Ω and 1000 Ω.

PROCEDURE

Resistance of a circuit element to passage of an electric current is determined simply by the measurement of current when a known voltage is placed across resistance.

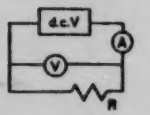


FIG. 23

1. Connect components of circuit as shown in circuit diagram (Figure 23). Be sure that voltmeter is connected directly across resistor, not across voltage supply unit. Use one of three resistors provided.

2. Vary voltage from zero to maximum value in approximately equal intervals, about eight steps in all, recording values of voltage and current each time, as read on meters. Record this data in Data Table 6.

3. Repeat for other two resistors.

4. Plot data for each resistor separately, but on one single sheet of graph paper. Place voltage values on vertical axis and current values on horizontal axis.

5. Determine resistance for each by measuring slope of each line. Remember that current must be expressed in amperes and potential difference in volts for the ratio V/I to give resistance in ohms. Record.

6. Compare results with manufacturer's value for resistors in Data Table 7.

DATA TABLE 6					
R_1		R_2		R_3	
V (volts)	I (ma)	V	I	V	I

DATA TABLE 7	
Value from Graph	Manufacturer's Value
R_1	
R_2	
R_3	

SELF CHECK

1. In a short paragraph, describe the concept of resistance and its affect in all energy systems. Include the final form of the energy expended to overcome resistance in all systems.

2. A 60-lb block can be pulled along at constant speed by a 15-lb force acting at an angle of 20° above the horizontal.

   a. How much of the 15 lb is lifting the block? How much is dragging it horizontally?
   b. What is the normal force — that is, the resultant force — pressing block and floor together.
   c. What is the coefficient of kinetic friction?

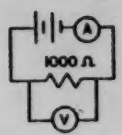
3. Only 12.5 lbs are required to pull a 50-lb crate at constant speed, but 15 lb to get it started. What are the coefficients of starting and of sliding friction?

4. Describe differences between laminar and turbulent fluid flow; give examples of the importance of streamlining.

5. A garden hose has a pressure drop of 5 lb/in^2 along its length when the water flow rate is 3 gal/min. Determine the following:

   a. The fluid resistance of the pipe.
   b. The pressure drop if the flow rate is increased to 5 gal/min. Assume laminer flow.

6. The resistance of a hydraulic line is 1.5 $lb/in^2/gal/min$. Determine the flow rate when the pressure drop is 4.5 lb/in^2.



7. A 1000-ohm resistor is placed in the circuit shown. Assume that the resistance of the battery and ammeter are negligible.

   a. What voltage is required to produce a reading of 1 ma by the ammeter A?
   b. What current is required to produce a reading of 6 volts by the voltmeter V?

8. When a 100-W light bulb is plugged into a 110V circuit, the current is 0.91A. What is the resistance of the light bulb?

9. A refrigerator must remove 2050 Btu's per hour from its interior to maintain an internal temperature of 35°F when the outside temperature is 95°F. Determine the following quantities:

   a. The thermal resistance of the refrigerator box.
   b. The thermal energy that must be removed each hour if the outside temperature is only 80°F.

10. The air frictional drag on a certain automobile is such that a force of 50 lb is required to keep it moving at a speed of 25 mi/h.

    a. Assume that the frictional force is proportional to the velocity. What is drag due to air resistance when the automobile is moving at 75 mi/h?
    b. Suppose that the automobile were poorly designed so that air friction varies as the square of the velocity. What is the drag due to the air at 75 mi/h in this case?

11. State the factors contributing to the following types of resistance and the affect each has upon resistance?

    a. Fluid resistance in long, straight pipes.
    b. Electrical resistance in wires.
    c. Thermal resistance in insulating materials.

12. Draw a graph showing resistance as the ratio of a forcelike quantity to a rate in the following energy systems:

    Fluidal.
    Electrical.
    Thermal.

13. State the fundamental difference between sliding friction and resistance in fluidal, electrical, and thermal systems.

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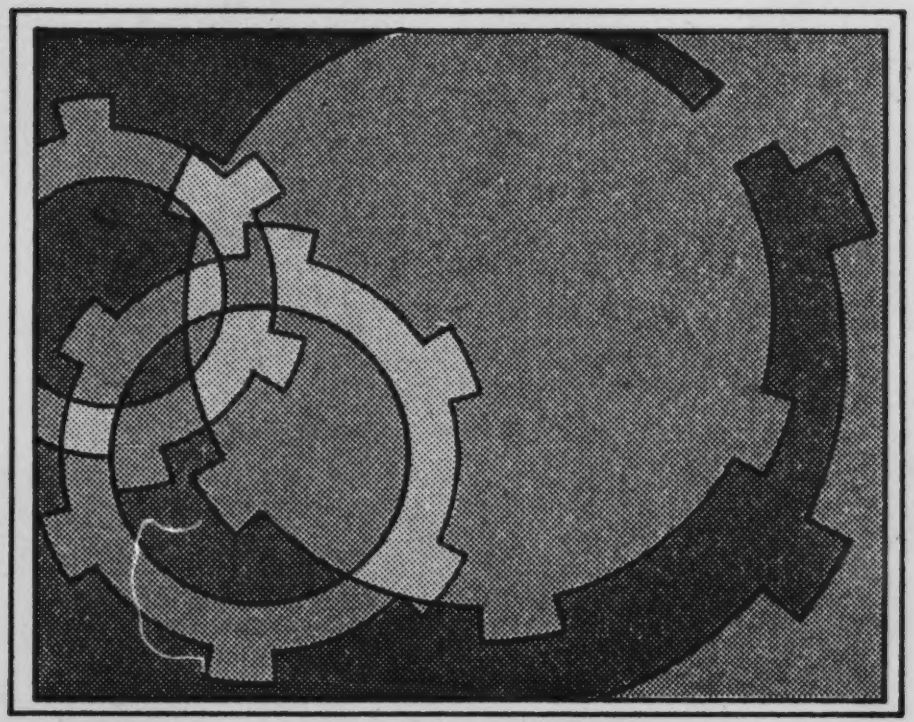
UNIFIED TECHNICAL CONCEPTS

MODULE 5 M 1

STATIC AND SLIDING FRICTION



MECHANICAL APPLICATION OF RESISTANCE

Technical Education Research Center - Southwest

TERC - SW

INTRODUCTION

Resistance occurs in all energy systems. This module will examine friction, the resistance in a mechanical energy system.

Friction is such a common phenomenon that its real importance is often overlooked. Many times, the effect of friction is undesirable. Lubricating oils are used in automobile engines specifically to reduce friction between moving parts. At other times, it is more important to increase friction. Lining materials in automobile brakes, for example, are carefully selected to increase the friction between moving parts.

This module will explain some of the factors that influence friction and will demonstrate a method of calculating the frictional force between a pair of surfaces in contact.

PREREQUISITES

Student should have completed Concept Module 5-0, "Resistance," and should have ability to solve algebraic relationships and use basic trigonometric relationships.

OBJECTIVES

To complete this module, the student should be able to:

- Define:
  - Force of static friction.
  - Force of kinetic friction.
  - Coefficient of static friction, μ_s.
  - Coefficient of kinetic friction, μ_k.
- Calculate the frictional force existing between two horizontal and two sloping surfaces in contact.
- Given the appropriate equipment, measure and record data needed to calculate the coefficient of friction between a given pair of surfaces.

- Calculate the work done to overcome static and kinetic friction between two given surfaces.

DISCUSSION

The term "friction" refers to the resistive force that opposes the relative motion of two surfaces in contact.

STATIC FRICTION

Consider a small block on the flat surface of a table as shown in Figure 1. Initially, the only forces acting on the block are the weight W and the normal force N perpendicular to the contact surfaces. A small force F is applied in an attempt to move the block across the table top. A frictional force f_s arises to oppose the motion. This frictional force is equal to the applied force, but opposite in direction. Because the two forces just balance on another, their vector sum is zero and the block does not move. As the applied force is increased, frictional force continues to increase so that the vector sum of these two forces remains zero. This condition is referred to as static friction. The force of static friction f_s is the force that resists the starting of one surface's movement across the other when the two are in contact.

Eventually, of course, a point is reached at which the static frictional force can no longer equal the applied force, and the block begins to slide. At the instant the block begins to slide, the system has reached the limit of static friction. The ratio of this maximum static frictional force $f_s(max)$ to the normal force pressing the surfaces together N is called the coefficient of static friction μ_s. This relationship is shown in Equation 1.

$$\text{Coefficient of static friction} = \frac{\text{maximum static frictional force}}{\text{normal force}}.$$

$$\text{In symbols:} \quad \mu_s = \frac{f_{s(max)}}{N} \qquad (1)$$

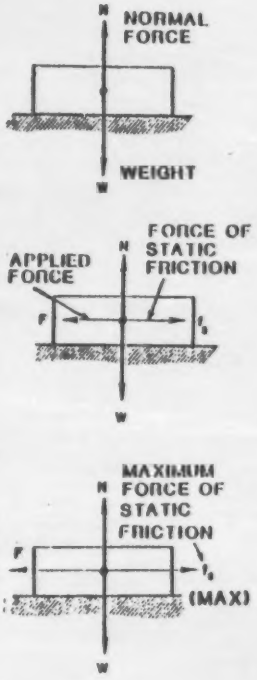


Fig. 1

KINETIC FRICTION

When the block begins to slide across the table top, resistance acting to retard the moving block is called the force of kinetic friction f_k. If just enough force is applied to maintain the sliding motion at a constant velocity, kinetic frictional force will be equal and opposite to applied force. The ratio of kinetic frictional force f_k to normal force N pressing the surfaces together is called the coefficient of kinetic friction μ_k.

This relationship is shown in Equation 2.

$$\text{Coefficient of kinetic friction} = \frac{\text{kinetic frictional force}}{\text{normal force}}.$$

$$\text{In symbols:} \quad \mu_k = \frac{f_k}{N} \qquad (2)$$

Coefficients for both static and kinetic friction can be experimentally determined for each given pair of surfaces. Engineering and physics handbooks and texts contain standard values for coefficients of friction. These values are based upon results of many tests. A list of coefficients of friction for several common materials is given in Table 1.

TABLE 1. APPROXIMATE VALUES FOR COEFFICIENTS OF FRICTION

Materials	Coefficient of Static Friction	Coefficient of Kinetic Friction
Wood on wood	0.50	0.30
Wood on stone	0.50	0.40
Steel on steel	0.15	0.09
Rubber on concrete	2.00	1.02
Wood on snow	--	0.04
Aluminum on snow	0.35	--
Brake lining on cast iron	0.40	--

Example A shows how the coefficient of static friction can be calculated using one of the formulas.

Example B shows how the coefficient of kinetic friction is used to solve a problem.

EXAMPLE A: FINDING COEFFICIENT OF STATIC FRICTION

Given: A wooden box weighing 90 pounds resting on a level wooden floor. A worker finds that the box must be pushed with a horizontal force of 45 pounds to just start the box in motion.

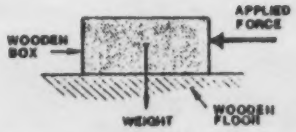
Find: Coefficient of static friction between box and floor.

Solution: Coefficient of static friction = $\frac{\text{static frictional force}}{\text{normal force}}$.

$$\mu_s = \frac{f_s\ (max)}{N}$$

$$= \frac{45\ lb}{90\ lb}$$

$$\mu_s = 0.50.$$



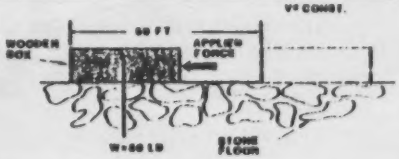
On a horizontal surface, normal force equals weight

Coefficient of static friction is 0.50.

EXAMPLE B: WORK AGAINST FRICTION

Given: A 50-lb wooden box on a level stone floor.

Find: How much work is done to push the box at a constant velocity for 50 ft along the floor.



Solution: Work is defined as applied force times distance. To move a box at a constant velocity, the applied force must just equal the force of kinetic friction.

a. Coefficient of kinetic friction = $\frac{\text{kinetic frictional force}}{\text{normal force}}$.

Normal force equals weight.

$$\mu_k = \frac{f_k}{N}$$

$$f_k = \mu_k \times N$$

$$= 0.40 \times 50\ lb$$

$$f_k = 20\ lb$$

Force of kinetic friction is 20 pounds.

b. Work = applied force x distance.

$$w = F \times s$$

$$= 20\ lb \times 50\ ft$$

$$w = 100\ ft\text{-}lb$$

100 foot-pounds of work is done pushing the box 50 feet.

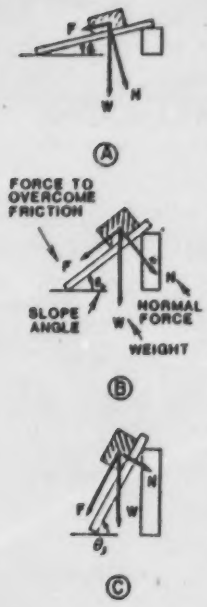


Fig. 2

The example problems just presented have included only horizontal contact surfaces. As a result, the normal force is always equal to the weight of the object. However, when an object is moved on a sloping surface, only a portion of its weight acts normal (or perpendicular) to the contact surface.

In fact, in the extreme case of a vertical slope, none of the object's weight is normal to the contact surface. Basic vector notation and trigonometry are needed to solve friction problems involving a sloping surface. Figure 2 introduces this notation.

In each of the cases shown in Figure 2, vectors are used to depict direction and magnitude of the force due to the object's weight W and its corresponding components: N, normal to the slope, and F, parallel down the slope. As can be seen, the greater the angle θ of the slope, the greater the value of F and the lesser the value of N.

As the normal force is defined as the force perpendicular to the contact surface, the angle between weight vector and normal vector is the same as the angle of the slope. Therefore a vector sketch of these forces forms a right triangle as shown in Figure 3, lending itself to solution by trigonometry.

By way of explanation, the cosine of an angle (from trigonometry) is defined as the ratio of the side adjacent to that angle divided by the hypotenuse, or longest side, of a right triangle. The sine of an angle is defined as the side opposite divided by the hypotenuse. Therefore:

$$\text{Cosine of slope angle} = \frac{\text{adjacent side}}{\text{hypotenuse}} = \frac{\text{normal force}}{\text{weight}}$$

or,

$$\text{Normal force} = \text{weight} \times \text{cosine of slope angle.}$$

$$\text{In symbols: } N = W \cos \theta \qquad (3)$$

Similarly,

$$\text{Sine of slope angle} = \frac{\text{opposite side}}{\text{hypotenuse}} = \frac{\text{force to overcome friction}}{\text{weight}}$$

or,

$$\text{Force to overcome friction} = \text{weight} \times \text{sine of slope angle.}$$

$$\text{In symbols: } F = W \sin \theta \qquad (4)$$

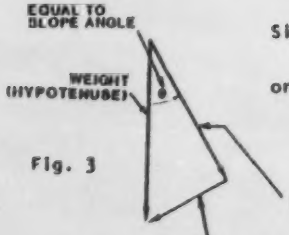


Fig. 3

NORMAL FORCE = WEIGHT X COSINE θ
(adjacent)

FORCE TO OVERCOME FRICTION = WEIGHT X SINE θ
(opposite)

Example C shows the solution to a problem involving a sloping surface.

EXAMPLE C: FRICTION ON A SLOPING SURFACE

Given: A 50-pound wooden crate on a wooden board inclined at a slope of 15 degrees.

Find: a. Normal force, N.
b. Force to overcome friction, F.
c. Maximum force of static friction, $f_s(max)$.
d. Will the crate slide due to its own weight?
e. At what angle of incline will the crate begin to slide due to its own weight?

Solution: a. $N = W \cos \theta$
$= (50 \text{ lb}) \cos 15°$
$= (50 \text{ lb})(0.966)$
$N = 48.3 \text{ lb}$

Normal force is 48.3 pounds.

b. $F = W \sin \theta$
$= (50 \text{ lb}) \sin 15°$
$= (50 \text{ lb})(0.259)$
$F = 12.94 \text{ lb}$

Force to overcome friction is 12.94 pounds.

c. $\mu_s = \frac{f_s(max)}{N}$

$f_s(max) = \mu_s \times N$
$= (0.50)(48.3 \text{ lb})$
$f_s(max) = 24.2 \text{ lb}$

Maximum static frictional force is 24.2 pounds.

d. Because F, the force to overcome friction, is less than $f_s(max)$, the crate will not slide down the incline.

e. The crate will not slide down the incline until F, the force to overcome friction, is equal to or greater than $f_s(max)$, the maximum force of static friction.

$$F \geq f_s(max)$$
$$W \sin \theta \geq \mu_s N$$
$$\sin \theta \geq \mu_s (W \cos \theta)$$
$$\frac{W \sin \theta}{W \cos \theta} \geq \mu_s$$
$$\tan \theta \geq \mu_s$$
$$\theta \geq \tan^{-1} \mu_s \text{ (Angle whose tangent is equal to } \mu_s.)$$
$$\theta \geq \tan^{-1} (0.50) = 26.6°$$

The angle is called the angle of repose. At this slope angle, the crate will just be on the verge of sliding down the incline.

$\frac{\sin \theta}{\cos \theta} = \tan \theta.$

HORIZONTAL SURFACES

MATERIALS

Board with a pulley similar to Central Scientific Company model 75845-000.
Wooden friction block similar to Central Scientific Company model 75860-000.
Weight hanger and assorted slotted weights.
Beam balance.
Short piece of string.
Friction blocks of various other materials as available.

PROCEDURE

1. Set up board and other equipment as shown in Figure 4.
2. Determine weight of wooden friction block; record in Data Table I as normal force.
3. Gently apply slotted weights to hanger until block starts to slide. (When block begins to approach point of sliding, slotted weights should be added in 5-gram increments or less.)
4. Determine total load that caused block to just begin sliding; record this in Data Table because it is equal to maximum force of static friction.
5. Calculate coefficient of static friction for surfaces by dividing maximum force of static friction by normal force.
6. Again set up board and other equipment as shown in Figure 4.
7. Gently apply slotted weights to hanger; at same time, give wooden block a slight push with finger or with tip of a pencil to start it in motion. Determine minimum load on weight hanger that will sustain motion of block at constant speed after it has been given an initial push. Record this load in Data Table I as force of kinetic friction.
8. Calculate coefficient of kinetic friction for surfaces by dividing force of kinetic friction by normal force.
9. Repeat 1 through 8 for friction blocks of various other materials as provided by instructor.

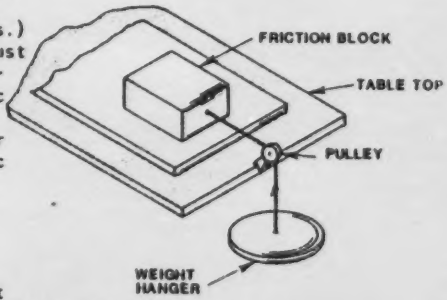


Fig. 4

DATA TABLE 1					
Material	Description Of Surfaces	Horizontal Normal Force* (Weigh)	Maximum Force Of Static Friction	Force Of Kinetic Friction	Coefficients Of Friction Static Kinetic
1					
2					
3					

*Force in dynes equals mass in grams times acceleration of gravity in centimeters per second per second.

$$1 \text{ dyne} = 1 \frac{g - cm}{s^2}$$

(Acceleration due to gravity) = 980 cm/s^2.

ANGLE OF REPOSE

MATERIALS

Board with a pulley similar to Central Scientific Company model 75845-000.
Wooden friction block similar to Central Scientific Company model 75860-000.
Beam balance.
Short piece of string.
Friction blocks of various other materials as available.

PROCEDURE

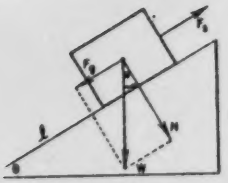


Fig. 5

1. Eliminate weight hanger from equipment used in part A. Arrange surfaces so that they may be elevated to a measurable angle.
2. With same materials and weights on block, elevate surfaces until block begins to slide down incline. This is called angle of repose and should be accurately measured and recorded in Data Table 2.

Figure 5 will help to explain how coefficient of static friction can be determined from angle of repose:

F_s = force of static friction.
F_g = force of gravity causing block to slide.
$F_s = F_g$ at instant block begins to slide.

$\mu_s = \frac{F_s}{N}$ from definition of coefficient of static friction. (5)

Notice also that in the force diagram,

$$\tan \theta = \frac{F_g}{N}$$

which is the same as

$$\tan \theta = \frac{F_s}{N} \quad (6)$$

because $F_g = F_s$.

Substitutions between Equations 5 and 6 yield:

$$\mu_s = \frac{F_s}{N} = \tan \theta$$

or

$$\mu_s = \tan \theta \quad (7)$$

To determine θ it is convenient to measure height and length of incline and use the relationship $\sin \theta = h/l$. Several trials should be averaged to determine an accurate value for h.

3. Use Equation 7 to determine coefficient of static friction for surfaces involved; record values in Data Table 2.
4. Calculate percent variation between values obtained in parts A and B for coefficient of static friction for each pair of surfaces involved. This can be done by using Equation 8.

$$\% \text{ variation} = \frac{\text{difference between values}}{\text{average of the values}} \times 100 \quad (8)$$

5. Compare values obtained experimentally with accepted values available in standard laboratory handbooks.

DATA TABLE 2				
Material	Description Of Surfaces	Weight	Angle Of Repose	Coefficient Of Static Friction
1				
2				
3				

SELF CHECK

1. Define:
   Force of static friction.
   Force of kinetic friction.
   Coefficient of static friction.
   Coefficient of kinetic friction.
2. A wooden crate weighing 150 pounds is to be pushed across a level stone floor. What horizontal force will be required to just start the crate in motion?
3. A sled weighing 500 pounds and equipped with wooden runners is to be pulled at a constant velocity across a level field of snow. How much work will be done when the sled is pulled a distance of 1000 feet?
4. A horizontal force of 20 newtons is required to slide a box of auto parts across level ground. What is the coefficient of sliding friction if the box has a mass of 420 kg?
5. A 500-lb block rests on a loading ramp inclined 15° from the horizontal. If the coefficient of static friction is 0.4, what force of static friction must be overcome to move the block down the ramp?
6. If the sides of a dry sand pile slide until they reach a 30° angle, what would the coefficient of static friction be for sand particles against other sand particles?

REFERENCES

Beiser, Arthur. Modern Technical Physics. 2nd ed. Menlow Park, CA: Cummings Publishing Company, 1973.
See especially Chapter 5.

Harris, Norman C. and Hemmerling, Edwin M. Introductory Applied Physics. New York: McGraw-Hill, 1972.
See especially Chapter 6.

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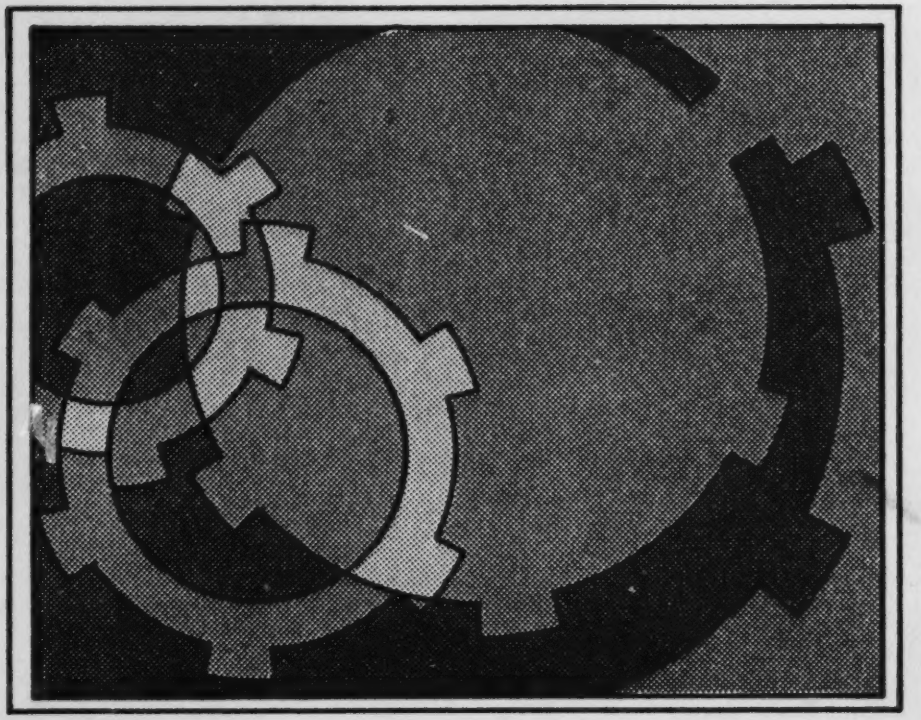
UNIFIED TECHNICAL CONCEPTS

MODULE 5 M 2

EFFECT OF LUBRICANTS



MECHANICAL APPLICATION OF RESISTANCE

Technical Education Research Center - Southwest TERC - SW

INTRODUCTION

When any two surfaces in contact move against each other, friction is present. The term "friction," as pointed out in Concept Module 5-0, refers to any resistance to this movement. In some applications, friction can be useful; in others, extremely harmful. Nails and screws depend upon friction to hold them in place. Fan belts and brakes are other examples of devices that depend upon friction to function properly. Friction in the moving parts of engines, on the other hand, can be very harmful. As friction in an engine increases, useful output power decreases. Increased friction causes heat, and heat causes expansion. Ultimately, if this heat is not removed, pistons or bearings may "freeze," or "lock up." In some cases, heat buildup may be sufficient to cause melting of bearings or other moving parts.

This module explains how lubricants overcome or reduce friction. It also lists some of the basic properties of lubricants. In the laboratory, the student will investigate the effects of various lubricants upon static and kinetic friction.

PREREQUISITES

Student should have completed Concept Module 5-0, "Resistance."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Define the coefficient of friction.
- List and explain three factors that contribute to friction.
- Define cohesion and adhesion, and describe how each is reduced by lubricants.
- List three common types of friction, and state which ones are reduced effectively by lubricants.
- State three reasons for lubricating moving parts.
- List three essential characteristics of lubricants.
- Given the appropriate equipment, demonstrate how the coefficient of friction is changed with the use of lubricants.

CAUSES OF FRICTION

There are three principal causes of friction in solids. They are:

Surface finish.
Cohesion and adhesion of molecules.
Weight or force holding the surfaces together.

SURFACE FINISH

Microscopic inspection of surfaces that appear smooth to the eye reveals surface irregularities. The interlocking of these irregularities prevents, because of friction, two surfaces from sliding over each other (with ease). Figure 1 shows what two relatively smooth surfaces look like if greatly magnified.

Surface finish of a material is a major factor in causing friction. These surface irregularities cause a grinding action as the surfaces move over each other. Motor oil in an automobile is changed periodically to remove the material ground off in this process. This grinding action also can cause considerable heating.

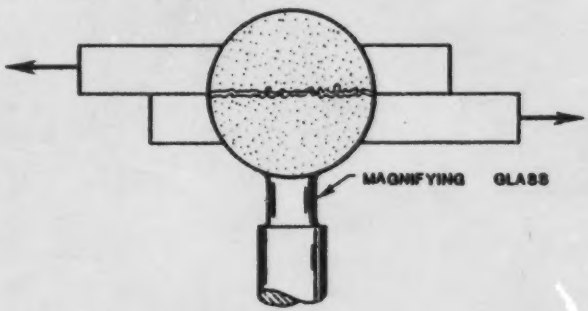


FIG. 1

MOLECULAR ATTRACTION

When two surfaces of the same type of material are in contact, molecules of one surface have an attraction for the molecules of the other surface. This attraction between like molecules is called "cohesion," which can be demonstrated by placing two pieces of flat glass against each other and pressing to remove the air between them. Cohesion will provide enough friction to make difficult the sliding of the top piece of glass. Cohesion causes friction in similar materials. Lubricants reduce cohesion by providing a film between the two surfaces.

Some surfaces of different materials will also have a molecular attraction when placed in contact. Molecular attraction between unlike molecules is called "adhesion." Glue, adhesive tape, tar and paint are well known for their adhesive properties.

Soaps and detergents are specially formulated so that they will break down adhesive forces and allow dirt and impurities to be washed away. Detergents are added to some lubricants in order that impurities can be dissolved and carried away from moving parts by the lubricants.

WEIGHT OR FORCE

Everyday experience shows that to drag a 200 lb bag of sand across a floor is more difficult than to drag a 100 lb bag. The force of friction that causes such objects to be difficult to slide is expressed by Equation 1.

$$f = \mu N \qquad (1)$$

where

f = force of friction.
μ = coefficient of friction.
N = normal force pressing the level surfaces together (weight).

Equation 1 shows that as normal force is increased, the force required to move the object is increased. Equation 1 is used in solving a problem in Example A.

EXAMPLE A: FORCE OF DRY SLIDING FRICTION	
Given:	A 150-pound metal tool box is pushed on a wood floor. There is a coefficient of friction value of 0.5 between the box and the floor.
Find:	The force required to keep the box sliding at a constant speed.
Solution:	$f = \mu N$ $= (0.5)\ (150)$ $f = 75$ pounds

KINDS OF FRICTION

There are three kinds of friction:

- Starting, or static, friction.
- Sliding, or kinetic, friction.

- Rolling friction.

Static friction is generally greater than sliding friction. Lubricants are effective in reducing static and sliding friction, but have little effect on rolling friction.

PURPOSE OF LUBRICANTS

Moving parts are lubricated to reduce friction, wear and heat. Lubricants are produced in many forms, the most common ones being oils, greases and graphite compounds. Each lubricant is used for a different purpose, but must meet three conditions:

- It must be able to withstand the heat generated during operation.
- It must flow freely and therefore keep a thin film between all moving parts.
- And it should prevent corrosion.

If a lubricant cannot withstand the heat of operation, it will soon vaporize or become so thin that its lubricating qualities are lost. Similarly, if a lubricant flows too slowly, it will not reach all the moving parts. Finally, if a lubricant causes a chemical reaction which corrodes the moving parts, it can cause permanent damage to the parts.

A lubricant separates moving parts and allows them to move on a thin film, as shown in Figure 2.

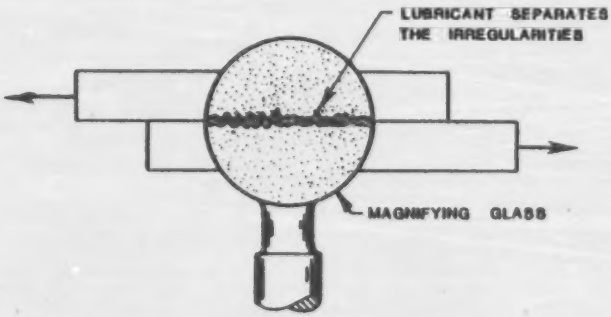


FIG. 2

SUMMARY

Lubricants help to overcome the resistance caused by friction between surfaces in contact. The most common lubricants are oils, greases, and graphite compounds - all of which must be able to withstand heat of operation, to flow freely and to prevent corrosion.

THE EFFECT OF LUBRICANTS UPON STATIC AND AND KINETIC FRICTION

MATERIALS

Three rectangular blocks, approximately 4" x 4" x 1", with one large smooth surface (aluminum, cast iron, steel).
One large aluminum plate (6" x 18" minimum).
Three lubricants: oil (light-grade), oil (heavy-grade) and grease.
Spring balance (scaled in dynes).

PROCEDURE

In the following experiment, the student will investigate the effect of various lubricants on static and kinetic friction, using several surfaces.

1. Place aluminum block on aluminum plate, as shown in Figure 3.

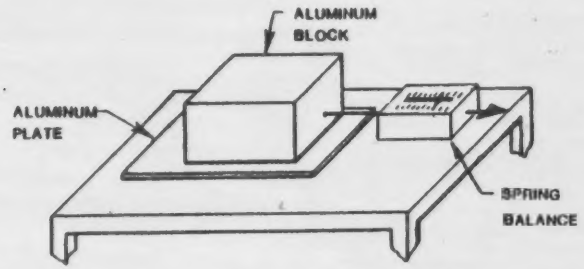


FIG. 3

2. Gently pull spring balance, and record in Data Table the static frictional force (f_s, in dynes) required to start block in motion.

3. Divide this force by weight (weight = mass x gravity) of the aluminum block. (In this case, normal force is just

weight of block.) The resulting number is the coefficient of static friction $\mu_s = \frac{f_s}{N}$.

4. Continue to pull aluminum block at a constant rate and record the required kinetic frictional force (f_k, in dynes). It should be less than f_s.

5. Divide this force by the weight of the aluminum block. This gives the coefficient of kinetic friction.
   $\mu_k = \frac{f_k}{N}$.

6. Replace aluminum block with cast iron, and repeat steps 1 through 5.

7. Replace cast iron with steel block, and repeat steps 1 through 5.

8. Record all values in appropriate boxes in Data Table.

9. Repeat previous steps in friction experiement, using grease as a lubricant on aluminum plate.

10. Calculate coefficient of static and kinetic friction, and record results in Data Table.

11. Remove grease from all parts, and clean surfaces. Dry all surfaces.

12. Repeat entire experiment using a thin film of heavy-grade oil as a lubricant.

13. Calculate coefficients of kinetic and static friction for this case, and record results in Data Table.

14. Again thoroughly clean and dry all parts.

15. Repeat the experiment, using a thin film of light-grade oil as a lubricant.

16. Calculate coefficients of static and kinetic friction as before, and record results in Data Table.

17. How do the three lubricants used in this procedure compare with reference to their effect upon friction?

DATA TABLE

	No Lubricant (Dry)			
Block	Static	μ_s	Kinetic	μ_k
Aluminum	F_s = _____		f_k = _____	
	N = _____		N = _____	
Cast iron	f_s = _____		f_k = _____	
	N = _____		N = _____	
Steel	f_s = _____		f_k = _____	
	N = _____		N = _____	

	Lubricant (Grease)			
Block	Static	μ_s	Kinetic	μ_k
Aluminum	f_s = _____		f_k = _____	
	N = _____		N = _____	
Cast iron	f_s = _____		f_k = _____	
	N = _____		N = _____	
Steel	f_s = _____		f_k = _____	
	N = _____		N = _____	

	Lubricant (Heavy-Grade Oil)			
Block	Static	μ_s	Kinetic	μ_k
Aluminum	f_s = _____		f_k = _____	
	N = _____		N = _____	
Cast iron	f_s = _____		f_k = _____	
	N = _____		N = _____	
Steel	f_s = _____		f_k = _____	
	N = _____		N = _____	

	Lubricant (Light-Grade Oil)			
Block	Static	μ_s	Kinetic	μ_k
Aluminum	f_s = _____		f_k = _____	
	N = _____		N = _____	
Cast iron	f_s = _____		f_k = _____	
	N = _____		N = _____	
Steel	f_s = _____		f_k = _____	
	N = _____		N = _____	

SELF CHECK

1. Write the equation defining the coefficient of friction, and identify each term.

2. Explain how each of the following contributes to frictional forces:

   Surface finish.
   Molecular attraction.
   Weight or pressure.

3. Define cohesion and adhesion, and explain how modern lubricants reduce each.

4. State the effect of lubricants on the three types of friction.

5. State three quantities that can be reduced by the use of lubricants.

6. List three essential characteristics of lubricants.

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Beiser, Arthur. Modern Technical Physics. 3rd ed. Menlo Park, CA: The Benjamin/Cummings Publishing Company, Inc., 1979.

Greenberg, Leonard H. Physics with Modern Applications. Philadelphia, PA: W.B. Saunders Company, 1978.

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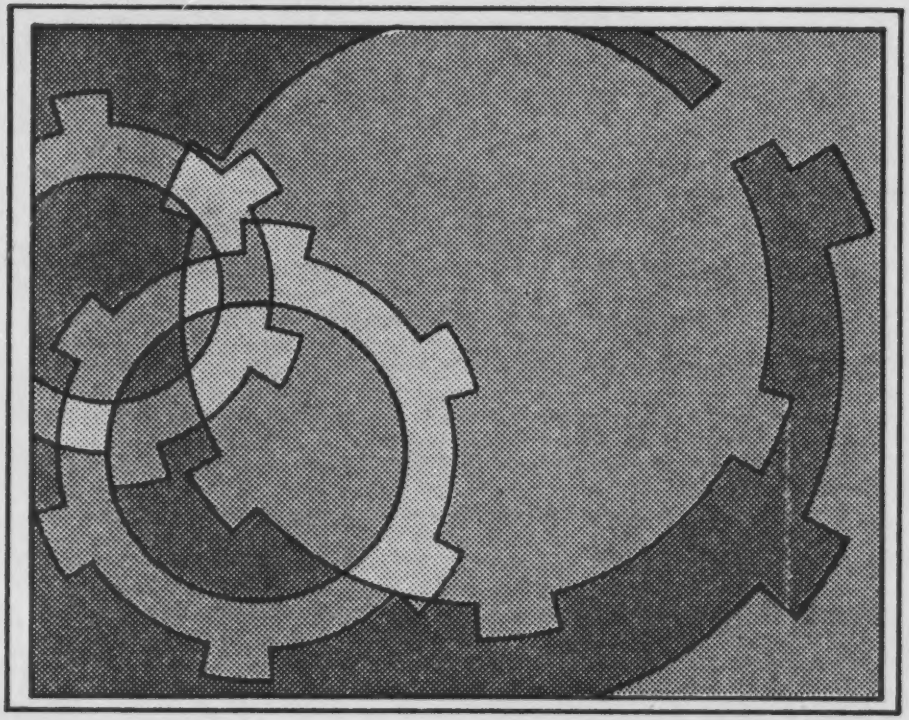
UNIFIED TECHNICAL CONCEPTS

MODULE 5 M 3

ROLLING FRICTION



MECHANICAL APPLICATION OF RESISTANCE

Technical Education Research Center - Southwest TERC - SW

INTRODUCTION

Friction is a form of resistance present in all moving mechanical systems. Although it may be reduced by several means, it cannot be eliminated completely. Friction in a system can be reduced effectively if sliding-friction components are replaced with rolling-friction ones.

The physical mechanisms that produce rolling friction and the relation of these mechanisms to sliding friction will be examined in this module. Methods of reducing rolling friction will be discussed. In the laboratory, the student will determine experimentally the coefficient of rolling friction for several mechanical systems.

PREREQUISITES

Student should have completed Concept Module 5-0, "Resistance."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Discuss the influence of surface irregularities on sliding and rolling friction.
- Describe surface deformation and its affect upon rolling friction.
- Define coefficients of static and rolling friction.
- Given a body and the horizontal forces applied through its center to start and maintain a constant rolling velocity, calculate its coefficients of static and kinetic rolling friction.
- Given the appropriate equipment, design and carry out an experiment to determine coefficients of static and rolling friction.

DISCUSSION

Figure 1 shows an enlarged view of the surfaces of two objects in contact. As described in Concept Module 5-0, "Resistance," even the smoothest surfaces have small irregularities. These tiny hills and valleys lock together to produce a physical barrier to motion. The resulting resistance is called "sliding friction."

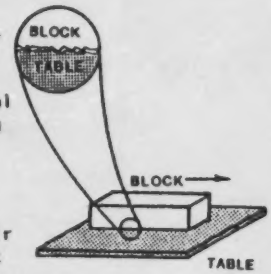


FIG. 1

Figure 2 shows how the effect of this type of friction is reduced when a round object rolls across a flat surface. The surface irregularities and friction still are present; but their effect is minimized, because the two surfaces do not slide. At the point of contact, they are motionless with respect to one another. The forward surface of the round object moves downward, causing the point of contact to move forward. At the same time, the rear surface is lifted away from the irregular surface of the flat object. Some friction still is present as the two surfaces make and break contact, but its affect is small compared with what is properly called "rolling friction."

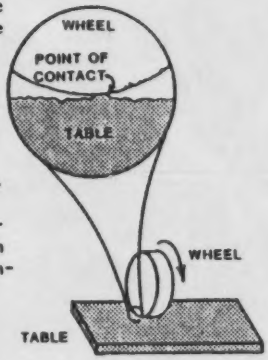


FIG. 2

Figure 3 illustrates the origin of rolling friction. In a real system, surfaces of the objects are not perfectly rigid, and some surface deformation occurs around the point of contact. At points A and B, the round object bulges slightly. From point C to point D, it is slightly flattened; and the plane surface on which it rests is indented. When the object rolls, both surfaces change shape as the point of contact moves forward. Internal resistance of objects to this change in shape produces rolling friction. Magnitude of the frictional force produced depends upon normal force between the objects and rigidity of their surfaces. Rigid surfaces (such as steel on steel) undergo less change in shape, producing smaller frictional forces than flexible surfaces, such as rubber on wood.

FIG. 3

Figure 4 shows the forces at work when a round object rolls across a plane surface at a constant velocity. The applied force F_a is horizontal and acts through the center of mass. The frictional force F_f is of equal magnitude, but opposite in direction. It acts tangent to the circular object at the point of contact. N is the normal force, equal and opposite to the weight of the round object. The torque produced by the force F_a about the point of contact causes the object to rotate. As with sliding friction, greater force is required to start the motion than to maintain it. The coefficients of static and kinetic rolling friction are defined by Equations 1 and 2.

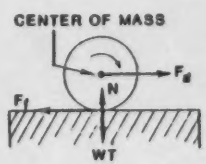


FIG. 4

$$\mu_s = \frac{F_s}{N} \qquad (1)$$

where

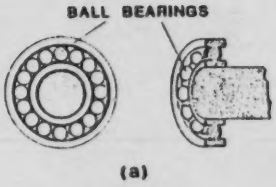
μ = coefficient of static rolling friction.

F_s = applied force to start rolling.
N = normal force.

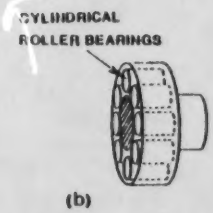
$$\mu_k = \frac{F_k}{N} \qquad (2)$$

where
μ_k = coefficient of kinetic rolling friction.
F_k = applied force to maintain rolling friction.

Example A shows how to use Equations 1 and 2 in solving a practical problem.



(a)



(b)

FIG 5

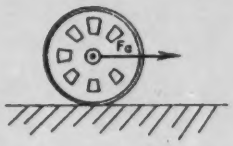
In most practical cases, these coefficients are much smaller than those of sliding friction. In addition, the difference between static and kinetic coefficients of rolling friction is less than the corresponding difference for sliding friction.

In many mechanical systems, sliding friction exerted on shafts rolling in plain bearings can be reduced drastially when roller or ball bearings are installed, thereby replacing the sliding friction by a lesser rolling friction. In sliding friction, resistance to motion is reduced if the sliding parts are separated with a thin film of lubricating oil. Use of rolling friction bearings, however, simplifies both the lubrication and the wear problems. In Figure 5, two common types of rolling friction bearings are shown, one with ball bearings and the other with roller (cylindrical) bearings.

EXAMPLE A: CALCULATION OF STATIC AND KINETIC FRICTION

Given: A 12-lb wheel is rolled across a wooden floor. A 9-ounce force is required to start it rolling, and a 7.5-ounce is required to keep it rolling at a constant velocity.

Find: Coefficients of static and kinetic rolling friction.



Solution: Static friction:

$$\mu_s = \frac{F_s}{N}$$

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$$\mu_s = \frac{(9\ \text{oz})\left(\frac{1\ \text{lb}}{16\ \text{oz}}\right)}{12\ \text{lb}}$$

$$= \frac{0.5625\ \text{lb}}{12\ \text{lb}}$$

$$\mu_s = 0.047$$

Kinetic friction:

$$\mu_k = \frac{F_k}{N}$$

$$= \frac{(7.50\ \text{oz})\left(\frac{1\ \text{lb}}{16\ \text{oz}}\right)}{12\ \text{lb}}$$

$$= \frac{0.469\ \text{lb}}{12\ \text{lb}}$$

$$\mu_k = 0.039$$

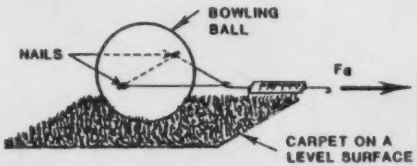
SUMMARY

Rolling friction (the resistance to rolling movement in a mechanical system) is not as great as other friction (the resistance of sliding friction). Ball and roller bearings — both of which exhibit rolling friction in movement — have little rotational resistance. The efficiency of a mechanical system is increased when components that exhibit high sliding friction are replaced with those that exhibit rolling friction.

DETERMINATION OF ROLLING FRICTION

MATERIALS

1-ft x 3-ft piece of pile carpet and 4 tacks.
Level wooden surface at least 1 ft x 3 ft.
Bicycle wheel.
Spring balance with 10-kg capacity.
Spring balance with 250-g capacity.
Set of metric weights with hangers.
Bicycle pump.
String with metal rings.
Bowling ball with axle as shown in Figure 6.
Note: . Axle is formed by drilling two small opposing holes in bowling ball and inserting a small finishing nail in each hole.



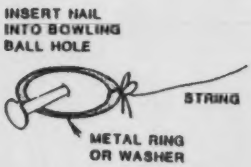


FIG. 6

PROCEDURE

1. Use large spring balance to weigh and determine masses of bowling ball and bicycle wheel. Record these values in Data Table.

2. Secure carpet on level surface with tacks. Place bowling ball on surface; attach small spring scale with string and metal rings as shown in Figure 6.

3. Apply a horizontal force F_a sufficient to cause ball to roll. Measure force necessary to start ball rolling and force necessary to keep ball rolling at a constant velocity. Record in Data Table. Note: Extreme care must be taken in measuring these small forces. Several attempts may be necessary to obtain reasonably consistent and accurate data.

4. Repeat step 3 on a wood surface without carpet; enter results in Data Table.

5. Set up bicycle wheel on wooden table as shown in Figure 7. Hang equal weights on opposite sides of wheel to bring total mass of wheel and weights to approximately 10 kg. Adjust air pressure in tire until tire is flattened noticeably at point of contact (trial 1, Figure 7).

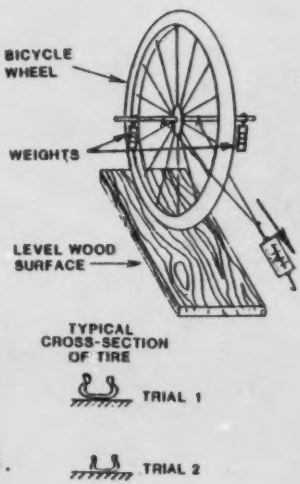


FIG. 7

6. Hold top of wheel lightly to balance it; apply a horizontal force F_a to cause wheel to roll. In Data Table, record forces necessary to start and maintain rolling.

7. Repeat step 6 with tire fully inflated; enter into Data Table.

8. Calculate coefficients of static and kinetic rolling friction, using Equations 1 and 2.

9. Are other sources of friction contributing to the rolling friction determined in each experiment? If so, identify their source, and determine whether sliding or rolling friction is involved.

DATA TABLE

Mass of bowling ball = _____ kg.
Mass of bicycle wheel = _____ kg.

Rolling Object	Mass (kg)	Rolling Surface	Type of Friction	Applied F_a Force (g)	Coefficient of Rolling Friction (Calculated)
Bowling ball		Carpet	Static		μ_s =
Bowling ball		Carpet	Kinetic		μ_k =
Bowling ball		Wood	Static		μ_s =
Bowling ball		Wood	Kinetic		μ_k =
Flat tire		Wood	Static		μ_s =
Flat tire		Wood	Kinetic		μ_k =
Inflated tire		Wood	Static		μ_s =
Inflated tire		Wood	Kinetic		μ_k =

SELF CHECK

1. Describe how small surface irregularities produce sliding friction.

2. Explain why surface irregularities do not contribute greatly

to rolling friction.

3. Write a one- or two-sentence definition for the coefficient of static and rolling friction.

4. In Figure 6, the mass of the ball is 7.25 kg, and the force necessary to start it rolling gives a scale reading of 180 g. Calculate coefficient of static rolling friction.

5. In Figure 7, mass of the wheel and weights is 9.68 kg and force necessary to keep it rolling is 95 g. Calculate the coefficient of kinetic rolling friction.

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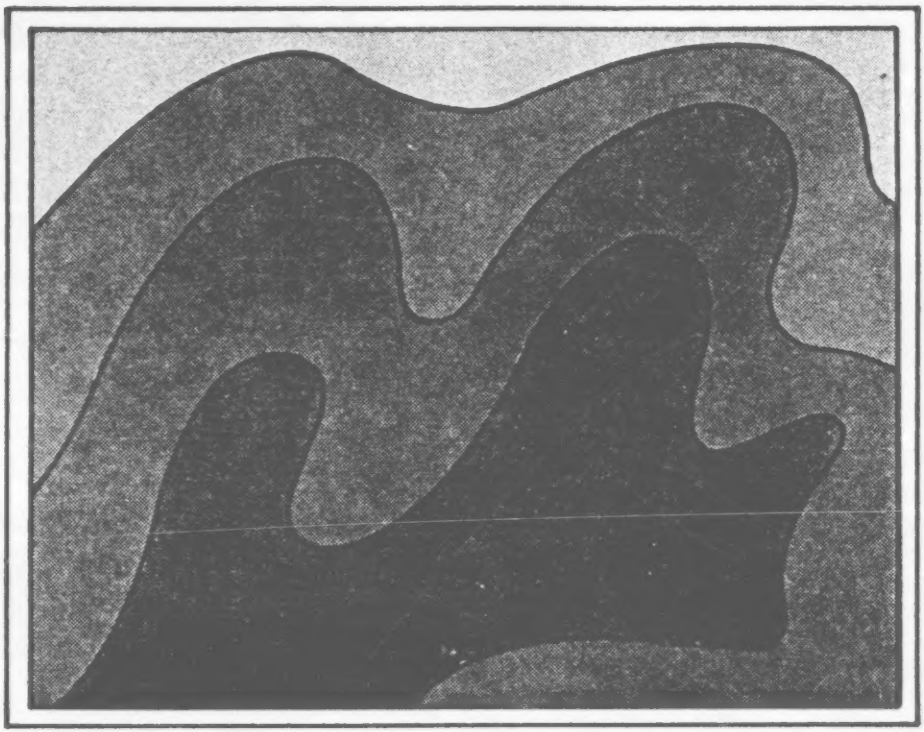
UNIFIED TECHNICAL CONCEPTS

MODULE 5 F 1

LAMINAR AND TURBULENT FLOW



FLUID APPLICATION OF RESISTANCE

Technical Education Research Center - Southwest

TERC - SW

INTRODUCTION

Flow is defined as the process by which a fluid is conveyed from one point to another through a pipe. The science of flow-meter engineering deals with the component parts of a flow system such as pumps, pipes and flow-measuring devices. A very important consideration when studying the flow of fluids is the classification of the flow as either turbulent or laminar.

PREREQUISITES

Student should have completed Concept Module 5-0, "Resistance," and Application Module 3F1, "Flow Rate Measurement With a Venturi Meter."

OBJECTIVES

To complete this module, the student should be able to:

- Calculate the Reynolds number (N_{Re}) of a flowing fluid given necessary variables.
- Given the Reynolds number determine whether the flow is laminar or turbulent.

TYPES OF FLOW

Two different types of fluid flow can occur in a pipe. They are laminar and turbulent.

Laminar flow is characterized by the gliding of concentric cylindrical layers over one another in an orderly fashion as shown in Figure 1. Maximum velocity of the fluid is at the center of the pipe; it decreases rapidly to zero at the pipe walls. In other words, if velocity at the center is represented as V_1 and velocity at the pipe walls as V_2, then V_1 is much greater than V_2 for true laminar flow. Heavy oils or other highly viscous fluids in pipes under low pressures will be characterized by laminar flow. Laminar flow is shown in Figure 2, where fluid velocity is plotted versus position.

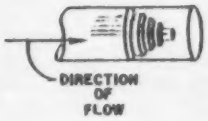


Fig. 1

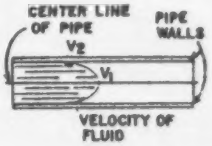


Fig. 2

Turbulent flow results when there is an irregular random motion of fluid particles to the main flow. A swirling (turbulent) action of the fluid is noted in this flow condition. The ratio of center velocity V_1 to the velocity at the pipe walls V_2 is $V_1/V_2 = 1$ for true turbulent flow. Velocity V_1 is equal to velocity V_2. The velocity is nearly uniform at every point throughout the pipe. Turbulent flow is illustrated in Figure 3.

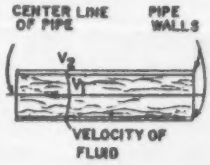


Fig. 3

A simple experiment can be used to illustrate the two different flow characteristics. To perform this experiment two things are needed:

- A fluid flowing through a transparent pipe. Water can be used.
- A means of injecting a small amount of a colored fluid into the flowing stream.

For laminar flow, which is sometimes called viscous or streamlined flow, the colored filaments will be carried along in undisturbed bands by the flowing water (Figure 4).

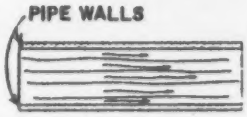


Fig. 4

There is a region between laminar and turbulent flow (Figure 5).

When a flow is turbulent, the colored filaments will be completely dispersed in the carrier stream a short distance downstream from the point of injection (Figure 6).

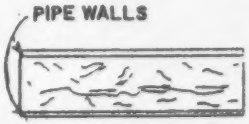


Fig. 5

This experiment provides a good method for empirically determining flow quality. It is sometimes advantageous, however, to predict for a given situation if the system will exhibit laminar or turbulent flow characteristics. To do this several parameters connected with the flow process must be known and used to calculate what is known as Reynolds number (N_{Re}). This tech-

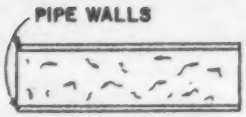


Fig. 6

nique was first developed by Osborn Reynolds who discovered that the nature of flow in pipe depends upon:

Pipe diameter.
Viscosity of the flowing fluid.
Velocity or amount of flow.

These three quantities are used in a formula to calculate the Reynolds number.

REYNOLDS NUMBER

The Reynolds number (N_{Re}) is a dimensionless ratio of the dynamic forces of mass flow to the shear stress of the flowing fluid caused by the viscosity of the material. N_{Re} is used to express the dynamic similarity of flow systems and is calculated from the formula shown in Equation 1.

$$N_{Re} = \frac{(6.32) \times (\text{rate of flow pounds/hour})}{(\text{pipe diameter in inches}) \times (\text{absolute viscosity in centipoise})} \quad (1)$$

As can be seen from the formula, the N_{Re} will vary with flow quantity, so flow quality is not only a function of physical characteristics, but also of dynamic properties.

Viscosity expresses the internal resistance of a fluid or its opposition to flow. It is a major factor in determining if a flow is laminar or turbulent. Viscosity of a fluid can be found in tables listing physical quantities of materials or by measurement, using laboratory instruments called viscometers. The metric unit of viscosity is the poise or centipoise (cP) (1 poise = 100 centipoise).

Kinematic viscosity is the ratio of the absolute viscosity used above to mass density of the fluid. When kinematic viscosity is used, no other correction for density is needed. The unit for kinematic viscosity is stokes or centistokes (1 stoke = 100 centistokes). For water, 1 stoke is about equal to a poise. A sample calculation for determining a Reynolds number is given in Example A.

Example A produced a very high N_{Re} and it signifies that the flow is turbulent. If conditions had been such that calculations yielded a N_{Re} lower than about 5000, flow would have approached laminar conditions (as shown in Example B).

EXAMPLE A: SAMPLE CALCULATION OF REYNOLDS NUMBER

Given: Water flowing at 70° F through a 2-inch pipe at a rate of 40 gal/min. Absolute viscosity = 1.0 centipoise (from tables).

Find: Whether flow is laminar or turbulent.

Solution:

$$N_{Re} = \frac{(6.32) \times (\text{rate of flow pounds/hour})}{(\text{pipe diameter in inches}) \times (\text{absolute viscosity in cP})}$$

To match the given information to the formula, it is necessary to convert the rate of flow from gal/min to pounds/hour.

$$40.0 \frac{\text{gal}}{\text{min}} \times \frac{60 \text{ min}}{1 \text{ h}} \times \frac{8.33 \text{ lb}}{1 \text{ gal}} = 19,992 \frac{\text{pounds}}{\text{h}}.$$

By plugging the values into the equation,

$$N_{Re} = \frac{(6.32)(19,992 \text{ lb/h})}{(2.00 \text{ in})(1.0 \text{ cP})} = \frac{126,349}{2.00} = 63,175.$$

Reynolds number is 63,175.

EXAMPLE B: CALCULATING REYNOLDS NUMBER

Given: Material: SAE 70 lube oil. Flow rate: 40 gal/min. Pipe size = 2 inch inner diameter. Viscosity = 2000 cP (from tables). Specific gravity = 0.916.

Find: Reynolds number.

Solution: Flow rate = (40 gal/min)(60 min/h)(8.33 lb/gal)(0.916)
= 18,313 lb/h.

$$N_{Re} = \frac{(6.32)(18,313)}{(2)(2000)} = \frac{115,738}{4000} = 28.9.$$

The plot shown in Figure 7 can be used to determine if flow conditions in a system produce laminar or turbulent flow.

The two examples given are for extreme situations producing very high and very low N_{Re}. The water flow system was turbulent and the oil flow system was laminar. In most practical flow situations, flow will be turbulent.

For a flow situation where the pipe characteristics are fixed, flow quality can change with changing rates and physical

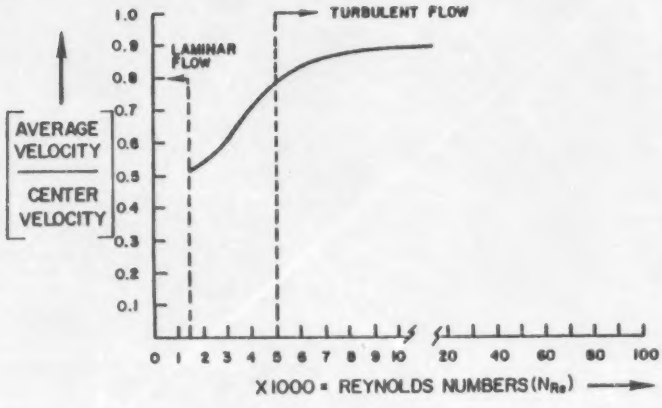


Fig. 7

conditions. The Reynolds number can be calculated and used as a sufficient criterion for dynamic similarity for flow systems.

FLOW MEASUREMENT

In the field of flow engineering, it is very important to know the quality of flow, and the Reynolds number is used to determine this. Most flow applications employ a "differential producer" and a device to measure the pressure drop across this restrictor. Flow rate is proportional to the square root of the pressure drop, and the pressure drop is related to velocity. The flow, then, is a function of velocity of a fluid flowing through a restrictor of known area. Pressure difference, which is caused by increase of the velocity through the restrictor, is measured at the pipe walls, and a velocity at the pipe center is inferred. It is necessary to know velocity at the center of the pipe because this is the restrictor location.

If flow measurement by this means is to be accurate, there must be an exact and constant ratio of average to center velocity of the flowing fluid. Turbulent flow is best suited for this situation. In fact, if a Reynolds number indicates that flow is either laminar or is in a region between laminar and turbulent (Figures 3 and 4), flow measurement cannot be made by the differential-producer method.

In industrial flow-metering applications, flow measurement is made largely by means of differential producers or head type flow measurement. A venturi is a head type flowmeter. When precise flow determination is necessary, correction factors are used to compensate for error caused by changes in viscosity or other flow variables which are factors in the degree to which a flow is turbulent. In actual calculations, the Reynolds number does not enter directly into the flow formula but instead is used to determine a Reynolds number correction factor F_c. The actual

flow formula used to relate flow to differential pressure is:

$$Q_n = C_n\sqrt{h_w}$$

where

Q_n = flow rate.
h_w = differential pressure.

$$Cn \text{ is a flow coefficient} = (K_s C_w F_a F_m \sqrt{\frac{G_f}{G_L}})\ F_c F_p$$

where

K_s = unit conversion factor.
C_w = coefficient for water flow rate at 1-inch differential.
F_a = factor for compensation or change in size of differential producer with temperature.
F_m = manometer correction factor.
G_f = specific gravity at flowing conditions.
G_L = specific gravity at standard conditions.
F_c = Reynolds number correction.
F_p = compressibility factor.

By holding all conditions constant, the only factor changing is F_c which changes as Reynolds number changes; this causes flow to be more or less turbulent. In actual practice, F_c is determined from N_{Re} and is used as a correction factor in the formula. Error in flow measurement caused by changing flow quality can result from changes in temperature, because a temperature change can alter the viscosity of the flowing fluid.

SUMMARY

For a given set of conditions, error in flow measurement caused by viscosity can be reduced by calculating a Reynolds number and then, from the Reynolds number, finding F_c. This value of F_c is entered into the flow equation and is then a factor in determining the relationship between flow and differential pressure across a differential producer - such as a venturi. When conditions vary and cause the flow quality to change from highly turbulent to less turbulent or even to laminar flow conditions, the error in flow measurement is compounded. The procedures in this exercise show this by changing flow material from a low vis-

cous quantity to a high viscous quantity.

Water used in procedure I has a viscosity of 1 centipoise at 60° F and produces a turbulent flow. Kerosene has a viscosity of 1.8 cP at 70° F and 3 cP at 40° F. By keeping all conditions except temperature equal, laminar flow should result when the viscosity is 3 cP. The 1.8-cP viscosity should produce a flow quality between laminar and turbulent.

MATERIALS

Glass venturi tube (18 cm long, 18 mm in diameter, tube narrows at center and has three outlet tubes at center. Ends of tube are flared.) (Suggested sources: Science Kit Inc. or Central Scientific Company.)
Two lengths of 3/4-in automobile heater hose.
Glass tubing for shaping manometer of appropriate commercial unit.
Rubber tubing (1/4-in inside diameter) for connections to outlet tubes of venturi.
Meter stick or metric scale.
Circular clamp for 3/4-in hose.
Two large containers (5-gallon buckets or trash cans).
Two platform scales graduated in kilograms (bathroom scales graduated in pounds may be used).
Stopwatch.
Small pump, able to deliver about 3 gal/min through a 1/2-in pipe.
Fluids with different values of viscosity (water and kerosene are suggested).
Needle valve to regulate amount of flow.
Assorted 1/2-in pipe fittings for connection of flow hardware.

PROCEDURE

1. Connect equipment as shown in Figure 8. Record weight of empty collection container.
2. Fill reservoir with water.
3. Start pump with exit hose in reservoir. Note: If pump is of reciprocating or positive displacement type, do not close needle valve fully, as this will cause excessive pressure and possibly damage the pump.
4. Set needle valve for low flow rate (approximately 0.5 gal/min). Record manometer reading.
5. Move exit hose to collection container for one minute.
6. Record weight of water transferred to collection container (measured weight - weight of container).
7. Return water to reservoir; repeat for

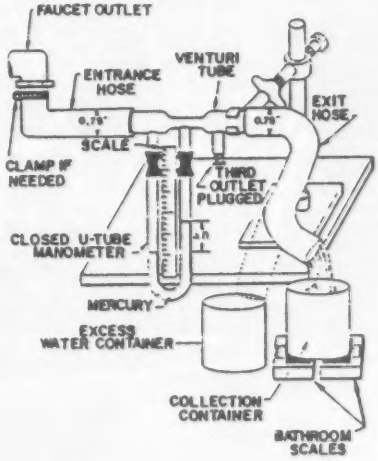


Fig. 8

four higher flow rates. Last data point should be with needle valve opened fully.

8. Repeat above procedure using kerosene at 70° F (viscosity = 1.8 cP). Set needle valve to give same five manometer readings as with water.
9. Repeat using kerosene at 40° F (viscosity = 3.0 cP).
10. Compare the three sets of data; explain reason for change in flow rate with same pressure differential.

DATA TABLE						
Trial		1	2	3	4	5
Water	Manometer differential (cm)					
	Fluid flow rate (lb/min)					
Kerosene At 70° F	Fluid flow rate (lb/min)					
Kerosene At 40° F	Fluid flow rate (lb/min)					

Weight of collection container = _____ lb.

SELF CHECK

1. If a fluid flows at 2 gal/min through a pipe with an 0.5 in inner diameter, what is the corresponding Reynolds number?
2. Would a fluid flowing through a pipe with a Reynolds number of 15,000 be laminar or turbulent.

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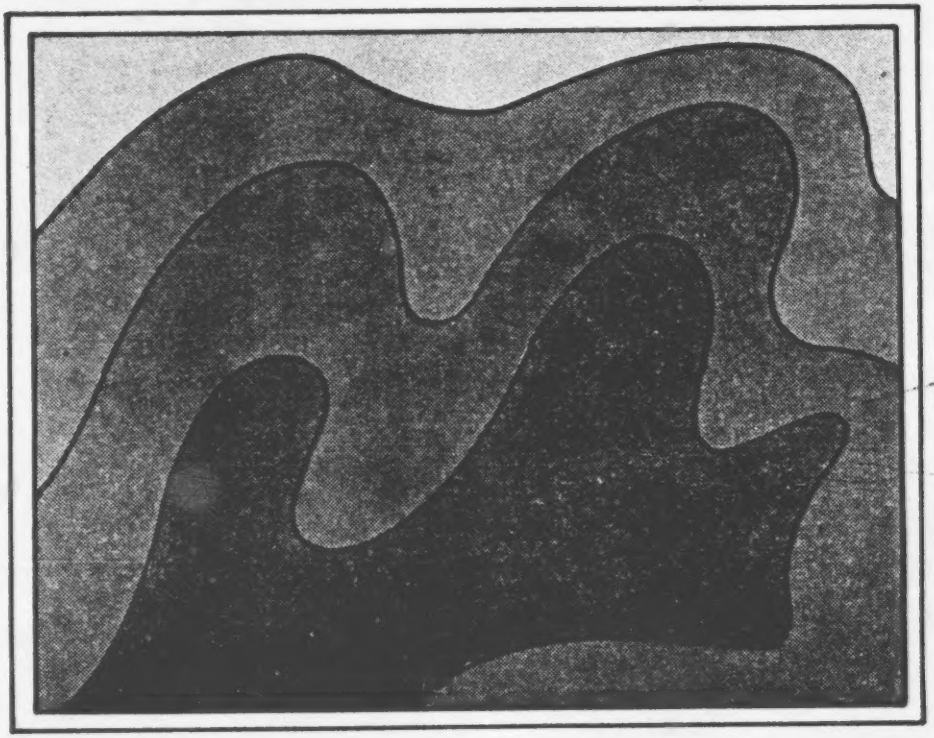
UNIFIED TECHNICAL CONCEPTS

MODULE 5 F 2

VISCOSITY



FLUID APPLICATION OF RESISTANCE

Technical Education Research Center - Southwest

TERC - SW

INTRODUCTION

The viscosity of a liquid can be described as internal resistance to motion of the liquid. It is the primary source of resistance when a liquid flows through a pipe, when an object moves through a liquid or when two surfaces separated by a lubricant move relative to each other. In this module the effects of viscosity in lubrication systems are presented. Methods of measuring viscosity and the effect of temperature on viscosity of lubricants also will be discussed. In the laboratory, the student will measure the viscosity of several lubricating oils at varying temperatures.

PREREQUISITES

Student should have completed Concept Module 5-0, "Resistance."

OBJECTIVES

Upon completion of this module, the student should be able to:

- State a two or three sentence definition of viscosity.
- Describe the flow of a lubricant between a moving and a stationary surface.
- List two advantages and three disadvantages of high viscosity lubricants.
- Describe in a short paragraph the effect of temperature on the viscosity of lubricants.
- Describe in two or three sentences, each of the following types of viscometers:

  Cup.
  Kinematic.
  Rolling sphere.

- Describe in a short paragraph the nomenclature used to indicate the viscosity of motor oils.
- Given the appropriate equipment, measure in the laboratory the relative viscosity of three motor oils at two temperatures.

DISCUSSION

The viscosity of a fluid is defined as the internal resistance to fluid flow. While the concept can be applied to gases, it is used more often as a description of resistance in liquid-flow systems. Higher viscosity means a greater resistance to flow. As an example, common motor oils have a higher viscosity than water, since they flow less easily than water. Concept Module 5-0, "Resistance," contains a discussion of how lubricants are used to reduce sliding friction between two surfaces. The resistance to motion present when a lubricant is used is due primarily to the viscosity of the lubricant. Figure 1 shows the flow of lubricant between a moving and a stationary surface. The lubricant forms thin layers that move relative to one another. The layer in contact with the moving surface moves at the same velocity as the moving surface. The next layer moves at a smaller velocity and the next at a still smaller velocity. The lubricant layer in contact with the stationary surface is itself stationary. The resistance to motion is the total resistance present as each layer of lubricant slides over the next.

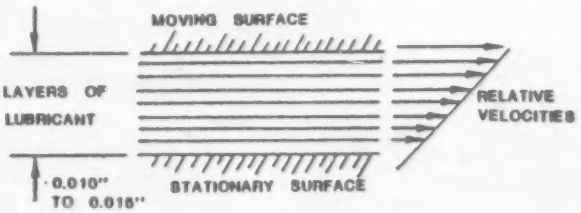


FIG. 1

The same phenomenon is present when a liquid flows through a pipe. In this case, the lubricant layers are concentric cylinders, with fluid velocity being greatest at the center of the pipe and decreasing to zero at the walls.

In mechanical systems, lubricants are chosen to provide minimum resistance for moving parts during normal operation. The details of lubricant choice are beyond the scope of this module, but the following characteristics will provide some insight into lubricant choice:

Higher viscosity lubricants flow less easily and will remain between moving parts longer than those of lower viscosity, which allows a lower rate of lubricant replacement.

High-viscosity lubricants provide a thicker oil film, which results in less friction for rougher surfaces. High-viscosity lubricants have greater internal resistance, which reduces their effectiveness at high speed.

The greater thickness of lubricant resulting from higher

viscosity is a barrier to heat flow.

Higher viscosity lubricants result in greater resistance in pipes and are more difficult to deliver and pump.

Another important consideration is the operating temperature of the lubricant. The viscosity of a liquid decreases as its temperature increases. The rate of decrease in viscosity with increasing temperature varies greatly from one liquid to another. In general, higher viscosity lubricants exhibit a greater change in viscosity over a given temperature range than lower viscosity lubricants.

VISCOSITY MEASUREMENT

Three types of instruments are commonly used for viscosity measurements. Each type of instrument is immersed in a temperature bath to stabilize the lubricant temperature at some standard value. The basic characteristics of each device, and the units commonly used to express viscosity for each, are discussed below. Figure 2 shows a cup viscometer. This device consists of a disk immersed in a cup containing the test liquid. The disk is rotated by a motor or spring, and the viscosity of the test liquid produces a resistance to the rotary motion. Similar instruments employ rotating cylinders, cones or paddles, depending upon the viscosity range of the fluid to be tested. Cup viscometers measure either the torque necessary to achieve a constant, rotational velocity or the velocity produced by a constant, applied torque. In either case, the unit of viscosity measure is usually the centistoke (1 centistoke = 1/100 stoke). The stoke is a complicated unit, which accounts for the force necessary to move a given surface area through a liquid at a given velocity. The density of the liquid also is included in the calculation. As a standard, the viscosity of distilled water at 20°C is 1.007 centistoke (cSt).

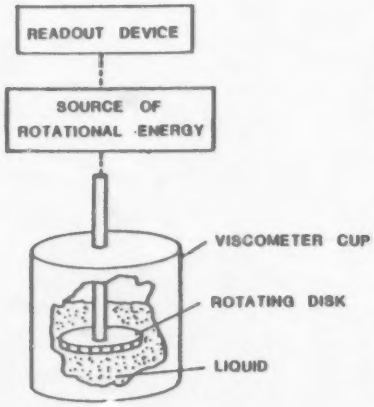


FIG. 2

Figure 3 shows one type of kinematic viscometer. In these devices, a known volume of liquid is placed in an open container with a calibrated outlet tube. The plug is removed from the tube, and the time required for the container to empty is measured. Several models of kinematic viscometers are in use; but the most common is the Saybolt Universal viscometer, in which 60 cm^3 of liquid flows through a capillary tube 1.225 cm long. The viscosity measured with this device is the time measured in Saybolt Universal Seconds (SUS), necessary for the container to empty.

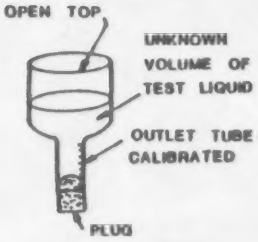


FIG. 3

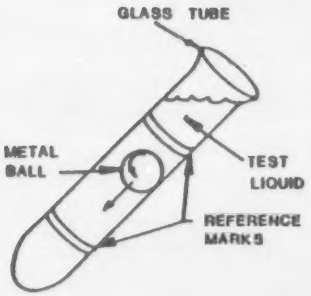


FIG. 4

A rolling sphere viscometer is shown in Figure 4. This device consists of a glass tube closed at one end and filled with the test liquid. A metal sphere with a diameter much less than the inner diameter of the tube is dropped in the upper end of the tube and rolls through the test liquid to the bottom. The time necessary for the ball to travel between two reference marks is measured. This time is divided by the time necessary for the ball to roll the same distance through some standard liquid to obtain the relative viscosity.

Since all these methods of specifying viscosity are difficult to apply in actual situations, the Society of Automotive Engineers adopted the SAE specification for automotive engine lubricants. The SAE number indicates the viscosity of the lubricant at a specific temperature. These values are given in Saybolt Universal Seconds in Table 1.

TABLE 1. SAE NUMBER / VISCOSITY

	Viscosity at - 18°C (0°F) SUS*		Viscosity at 99°C (210°F) SUS*	
SAE No.	Min.	Max.	Min.	Max.
5W	---	4,000	--	--
10W	6,000[a]	<12,000	--	--
20W	12,000[b]	48,000	--	--
20	---	---	45	<58
30	---	---	58	<70
40	---	---	70	<85
50	---	---	85	110

[a]Minimum viscosity at - 18°C (0°F) may be waived if viscosity at 99°C (210°F) is not less than 40 SUS.

[b]Minimum viscosity at - 18°C (0°F) may be waived provided viscosity at 99°C (210°F) is not less than 45 SUS.

*SUS - Saybolt Universal Seconds.

In the SAE nomenclature system, numbers followed by the letter W indicate low temperature lubricants and those without the W indicate high temperature lubricants. The larger the SAE number, the higher the viscosity. Multi-grade engine oils are blended to have a lower change in viscosity with increasing temperature than single grade oils. Thus, SAE 10W-40 has the viscosity of SAE 10W oil at -18°C and the viscosity of SAE 40 oil at 99°C, which provides proper lubrication during normal operation, but reduces lubricant resistance for starting cold engines.

SUMMARY

Viscosity is the internal friction, or resistance to motion, of a fluid. Higher-viscosity lubricants flow less easily than those of lower viscosity, but have a thicker oil film, greater internal resistance, and greater barrier to heat flow. Various pieces of equipment require lubricants having a specific viscosity.

DETERMINING VISCOSITY OF LUBRICANTS AT VARYING TEMPERATURES

MATERIALS

Water.
SAE 10W oil.
SAE 40 oil.
SAE 10W-40 oil.
Standard wall glass tubing, 25 mm outer diameter, 50 cm long, one end closed, calibration marks 40 cm apart.
Test tube holder.
1/4 inch diamter steel ball bearing.
1 liter beaker.
Hot plate.
Thermometer.
Lab timer.

PROCEDURES

1. Place all oil in refrigerator overnight to lower temperature.
2. Mount glass tube in test tube holder, as shown in Figure 5. (Angle of inclination of tube with horizontal is 10°.)
3. Fill tube with water to within 1 cm of top.
4. Insert thermometer; measure and record water temperature in Data Table.
5. Drop ball bearing into open end of tube. Measure and record time for ball to roll between two reference marks.
6. Remove tube from test tube holder; empty tube, and dry thoroughly. Do not change orientation of test tube holder; that is, do not change inclination from 10° standard arranged in step 2.
7. Pour about half a quart of cooled SAE 10W oil into beaker; measure and record temperature.
8. Replace tube; fill with SAE 10W oil.
9. Drop ball into open end of tube. Measure and record time for ball to roll between two reference marks.

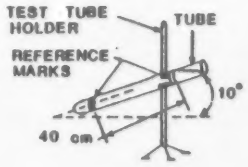


FIG. 6

10. Return SAE 10W oil to beaker. Heat over hot plate to about 100°C. Measure and record oil temperature. (Caution: Hot oil can cause severe burns. Handle with care.)

11. Return heated SAE 10W oil to tube, and repeat measurement. Record time in Data Table.

12. Remove oil from tube, and clean tube thoroughly.

13. Repeat steps 7 through 12 with SAE 40 and SAE 10W-40 oil.

14. Divide each time recorded by the time measured for water to determine viscosity of oil relative to that of water.

15. Explain the relationship between viscosity and temperature of each lubricant tested.

DATA TABLE			
Liquid	Temperature (°C)	Time (s)	Relative Viscosity
Water			1.00
SAE 10W	(Cold)		
SAE 10W	(Hot)		
SAE 40	(Cold)		
SAE 40	(Hot)		
SAE 10W-40	(Cold)		
SAE 10W-40	(Hot)		

SELF CHECK

1. Viscosity is a measure of what characteristic of a liquid?

2. Draw and label a diagram illustrating the flow of a lubricant between a moving and a stationary surface.

3. Describe two problems that would result from using a more viscous motor oil than that for which an engine is designed.

4. What happens to the viscosity of the motor oil as an automobile engine warms up?

5. Name each of the following viscometers:

   a. A disk or cylinder is rotated in a cup of liquid and torque is measured.
   b. A liquid flows from a reservoir and the time required is measured.
   c. A metal sphere rolls down a tube filled with a liquid and the time for a specified distance is measured.

6. Describe the differences between each of the following pairs of motor oil:

   a. 20 and 20W.
   b. 30 and 10W-30.

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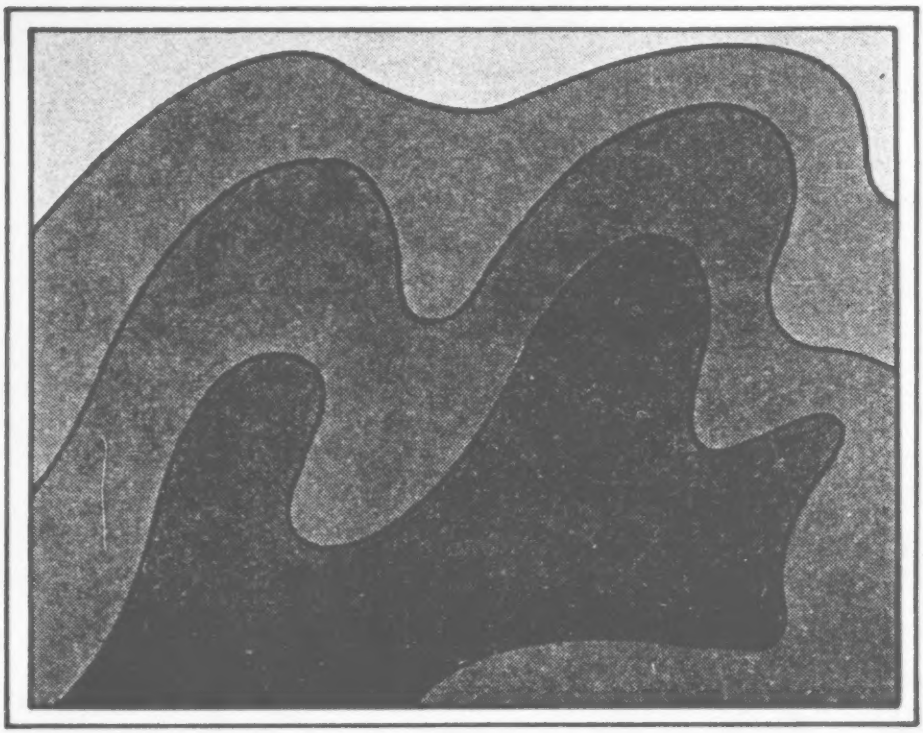
UNIFIED TECHNICAL CONCEPTS

MODULE 5 F 3

FLUID RESISTANCE IN PIPES



FLUID APPLICATION OF RESISTANCE

Technical Education Research Center - Southwest

TERC - SW

INTRODUCTION

There are many causes for energy losses in any system that uses fluid power. The major cause of energy loss in a fluid-power system is friction. Concept Module 5-0 explained that this friction is due to the fact that the fluid molecules bump against one another and against the pipe walls. Friction produced in this manner is manifested as heat given off to the surrounding air or to some cooling media. Heat always represents a loss of energy in a fluid-power system. This loss always shows up as a decrease in head, or pressure, across the system and is labeled as a frictional loss, or frictional drop. In the laboratory, the student will investigate how the friction losses in a pipe are affected when the pipe's length or diameter is changed and when the viscosity of the fluid that flows through it is changed.

PREREQUISITES

Student should have completed Concept Module 5-0, "Resistance."

OBJECTIVES

Upon completion of this module, the student should be able to:

- List the four factors that affect fluid flow rate through a pipe, and state how changes in each of these affect fluid flow rate.
- Draw and label diagrams, showing fluid flow rate as a function of each of the above quantities.
- Draw and label a diagram of pressure differential as a function of fluid flow rate, and identify the streamline and turbulent regions.
- Explain why streamline flow usually is employed in fluid power systems.
- Given the absolute viscosity of a fluid, the flow rate through a pipe, and the pipe length and diameter, calculate the pressure differential of the pipe.

- Given the absolute viscosity of a fluid, the pressure differential across a pipe and the pipe length and diameter, calculate the fluid flow rate for laminar flow.

- Given the appropriate equipment, determine (1) the head loss of a fluid flowing through various lengths and diameters of straight pipe, and (2) the affect produced upon the head loss when two fluids of differing viscosity are used.

DISCUSSION

Fluid flow in a pipe always is accompanied by the friction of fluid molecules colliding with one another and with the walls of the pipe; and consequently, by the loss of energy available to do work. Another way of stating this is that there must always be a pressure drop in the direction of flow, as illustrated in Figure 1.

If the valve in Figure 1 is closed, there is no fluid flowing in the pipe. Thus, the pressure p_1 is the same as p_2, and both are equal to the head of liquid in the cylinder, as shown by Equation 1.

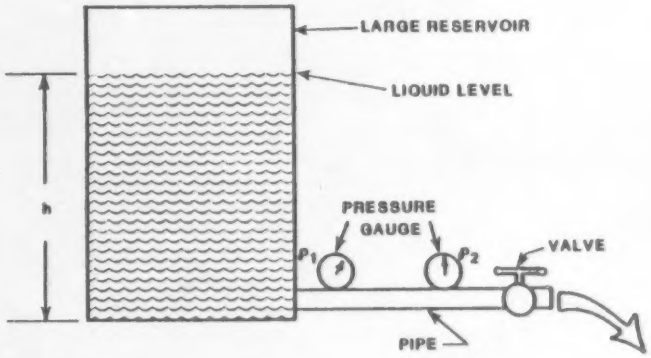


FIG. 1

$$p_1 = p_2 = \rho gh \qquad (1)$$

where

$p_1 = p_2$ = pressure in lb/ft^2.
ρg = weight density of liquid in lb/ft^3.
h = depth of liquid in ft.

Example A shows the use of this equation in solving a problem.

EXAMPLE A: CALCULATING LIQUID HEAD

Given: The depth of water in a barrel is 2 ft.

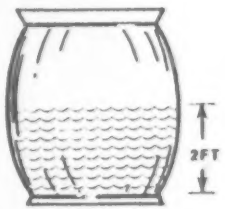
Find: Pressure at the bottom of the barrel.

Solution: Water has a weight density of $\rho g = 62.4\ lb/ft^3$.

$$p = \rho gh$$

$$= (62.4\ \frac{lb}{ft^3})(2\ ft)$$

$$p = 124.8\ \frac{lb}{ft^2}$$



Or, if the pressure is to be in lb/in^2 –

$$p = 124.8 \frac{lb}{ft^2} \left(\frac{1\ ft^2}{144\ in^2}\right)$$

$$p = 0.866 \frac{lb}{in^2}$$

If the valve in Figure 1 is opened, allowing the liquid to flow, pressure p_2 is less than pressure p_1. This pressure drop is caused by the fluid resistance in the pipe.

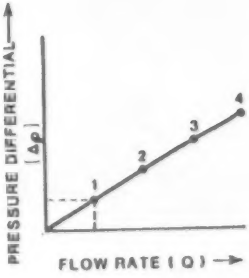


FIG. 2

As stated in Concept Module 5-0, "Resistance," if the outflow of water is collected and measured for a measured time interval, the flow rate of the liquid at a constant pressure can be determined. This constant pressure is simply the liquid head shown in Figure 1 and is assumed to be constant if the reservoir level does not drop too much during the collecting time. This flow rate and pressure differential Δp is shown in Figure 2 as point 1.

If this experiment is repeated for progressively greater depths of liquid, the flow rate increases linearly for greater pressure differential Δp; thus, points 2, 3, and 4 of Figure 2 are obtained. The resulting graph shows how pressure differential (forcelike quantity) across a pipe changes with fluid flow rate through the pipe. Concept Module 5-0, "Resistance," stated that the plotting of a forcelike quantity against a rate produces a graph in which the slope of the line at any point is a measure of the resistance offered by the system for that flow rate.

As long as the flow rate increases linearly with the pressure differential Δp, the liquid flow in the pipe is laminar (streamlined). A point soon is reached, however, when the pressure that pushes the fluid through the pipe increases so much that the flow becomes turbulent. When turbulent flow sets in, the resistance increases, and greater pressure is required to increase the flow rate from this point onward.

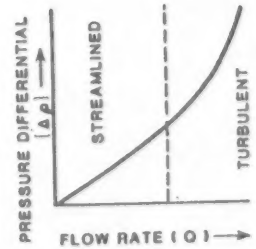


FIG. 3

Figure 3 shows the affect of turbulence upon the pressure required to move liquid through a pipe at a given rate. Since the slope represents resistance, in the turbulent region the resistance obviously is increasing continuously; and ever-larger pressure differentials are required to increase the flow rate.

The point at which fluid flow becomes turbulent can be determined from the Reynolds number, given by Equation 2.

$$N_R = \frac{6.32\,Q}{d\eta} \qquad (2)$$

where

Q = flow rate (lb/h).
d = pipe diameter (in).
η = absolute viscosity (centipoise).

If the Reynolds number is less than 5000, the liquid flow probably will be laminar. For Reynolds numbers greater than 5000, the fluid flow will be turbulent. Examples B and C illustrate the use of Reynolds number to determine whether fluid flow is laminar or turbulent.

EXAMPLE B: CALCULATION OF REYNOLDS NUMBER

Given: Water is flowing in a 1-inch pipe at a rate of 4 gal/min. The absolute viscosity of water is η = 1 centipoise.

Find: Whether the fluid flow is laminar or turbulent.

Solution: Weight density of water = 8.33 lb/gal.

$$Q = (40\ \text{gal/min})\left(\frac{60\ \text{min}}{\text{h}}\right)(8.33\ \text{lb/gal})$$

$$Q = 19992\ \text{lb/h}$$

$$N_R = \frac{6.32Q}{d\eta}$$

$$= \frac{(6.32)(19992\ \text{lb/h})}{(1\ \text{in})(1.0\ \text{cp})}$$

$N_R = 126349$ (Notice that all units are dropped in calculating N_R.)

Since $N_R \gg 5000$, the flow is turbulent.

EXAMPLE C: CALCULATION OF REYNOLDS NUMBER

Given: Motor oil is flowing in a 1-inch pipe at a rate of 40 gal/min. The viscosity of the motor oil is 2000 cp, and the specific gravity is 0.916.

Find: Whether the fluid flow is laminar or turbulent.

Solution:

$$Q = (40 \text{ gal/min})(60 \text{ min/h})\left(\frac{8.33 \text{ lb}}{\text{gal}}\right)(0.916)$$

$$Q = 18313 \text{ lb/h}$$

$$N_R = \frac{6.32\,Q}{d\eta}$$

$$= \frac{(6.32)(18313 \text{ lb/h})}{(1 \text{ in})(2000 \text{ cp})}$$

$$N_R = 57.87$$

Since $N_R \ll 5000$, the flow will be laminar.

Since virtually all practical fluid f[illegible] systems operate in the streamline region of Figure 3, the remainder of this module will discuss only streamline flow. For streamline flow, the flow rate Q and the pressure differential Δp are related by Equation 3.

$$Q = \frac{1176\,d^4}{\eta \ell}\,\Delta p \qquad (3)$$

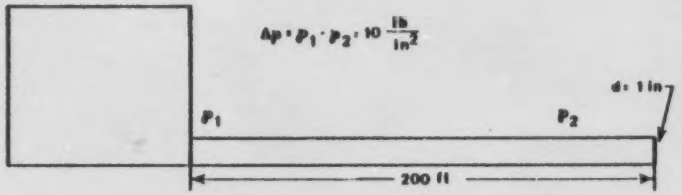
where

Q = flow rate (gal/min).
d = pipe diameter (in).
η = absolute viscosity (centipoise).
ℓ = pipe length (ft).
Δp = pressure (lb/in^2).

Example D shows the use of this equation to calculate flow rate through a pipe.

EXAMPLE D: CALCULATION OF FLOW RATE

Given: Water is flowing through a pipe 1 inch in diameter and 200 ft in length. The pressure differential along the pipe is 10 lb/in^2.



Find: The flow rate.

Solution: $Q = \frac{1176\ d^4}{\eta \ell} \Delta p = \frac{(1176)(1)^4(10)}{(1)(200)}$

$Q = 58.8$ gal/min.

Notice that the units are not used in this calculation. The value 1176 is chosen to give the flow rate in gal/min if all other quantities are expressed in the units specified for the equation.

Equation 3 states that the flow rate of a viscous fluid through a tube is directly proportional to the pressure difference between the ends of the tube; directly proportional to the 4th power of the diameter of the tube; and inversely proportional to both the length of the tube and the viscosity of the fluid. Now the affect on flow rate when each of these quantities is varied independently of the others shall be presented.

Figure 4 shows flow rate as a function of pressure differential for a fixed pipe length and diameter and for a fixed fluid viscosity in the laminar flow region. The flow rate increases linearly with the pressure differential. A change in the value of any of the fixed quantities will produce another straight line with a different slope. The dotted line, for example, shows flow rate as a function of pressure differential for a pipe of smaller diameter. The same effect could have been achieved by use of a greater pipe length or a fluid of higher viscosity.

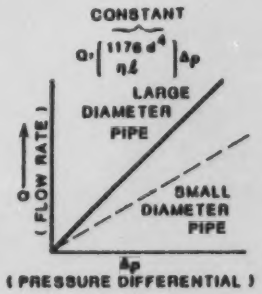


FIG. 4

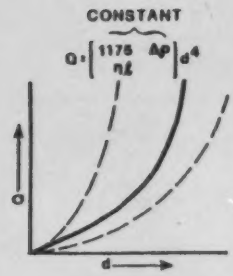


FIG. 5

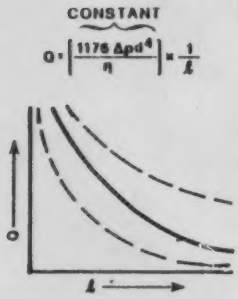


FIG. 6

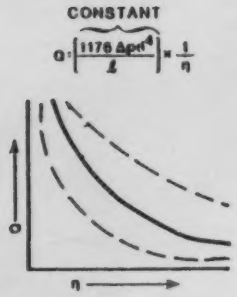


FIG. 7

In Figure 5, all quantities in Equation 3 are held constant, except the pipe diameter. In this case, flow rate increases as the fourth power of diameter. A change in the value of any of the fixed quantities results in a curve of the same general shape as indicated by the dotted lines in the figure.

Variation of only the length of the pipe results in the graph shown in Figure 6. In this case, doubling of the pipe length cuts the flow rate in half and the curve approaches zero asymptotically.

Figure 7 shows similar curves that result when fluids of differing viscosity flow through the same pipe. These curves have the same shape as those in the graph of flow rate versus pipe length in Figure 6.

If Equation 3 is rearranged to express pressure differential in terms of the other quantities, the result is Equation 4.

$$\Delta p = \left[\frac{\eta \ell}{1176\ d^4}\right] Q \qquad (4)$$

This equation states that the forcelike quantity Δp is the product of some constant (that depends upon the exact pipe and fluid) and the fluid flow rate. The form of this equation is the same as for Ohm's Law in electrical systems. The quantity $\left[\frac{\eta \ell}{1176\ d^4}\right]$ can be thought of as the resistance-like term; in fact, the electric resistance of a wire is given by:

$$R = \frac{\rho \ell}{A} = \frac{\rho \ell}{(\pi/4) d^2}$$

where

ρ = resistivity.
ℓ = length of resistor.
A = area of resistor $\frac{\pi}{4} d^2$.

The "resistance" of fluid flowing through a pipe is then

$$\text{"R"} = \frac{\eta \ell}{1176\ d^4}$$

This similarity is shown in Figure 8.

Unifying Equation:

FORCELIKE QUANTITY = RESISTANCE TERM X RATELIKE QUANTITY

Electrical Systems:

Voltage = Resistance x Current

$$V = RI$$

$$V = \left[\frac{4\rho\ell}{\pi d^2}\right] I$$

Fluid Systems:

Pressure differential = Resistance x Flow Rate

$$\Delta p = RQ$$

$$\Delta p = \left[\frac{\eta\ell}{1176\ d^4}\right] Q$$

FIG. 8

SUMMARY

Fluid flow in pipes may be either streamlined (laminar) or turbulent. In the laminar flow region, the resistance to flow is a constant; thus, a constant fraction of system power is needed to overcome this resistance. For turbulent flow, resistance always is higher than for laminar flow; and the resistance increases further as flow rate increases. Thus, a greater fraction of total system power therefore is used to overcome resistance. Fluid power systems usually are designed to operate with laminar flow, because of the higher efficiency afforded by lower resistance.

Factors affecting the fluid flow rate in a pipe are pressure differential, pipe diameter, pipe length, and fluid viscosity. Connectors, restrictions, valves, and bends in pipes also affect fluid flow in practical systems.

FLUID RESISTANCE IN PIPES

MATERIALS

Large tank with outlet near base.
Three pieces of glass tubing with diameters and length ratios shown in Figure 9.
Matching-bore rubber tubing.
A scale for weighing the fluid.
One quart container.
Clamp for rubber tubing.
2 types of fluid, preferably water and light oil.

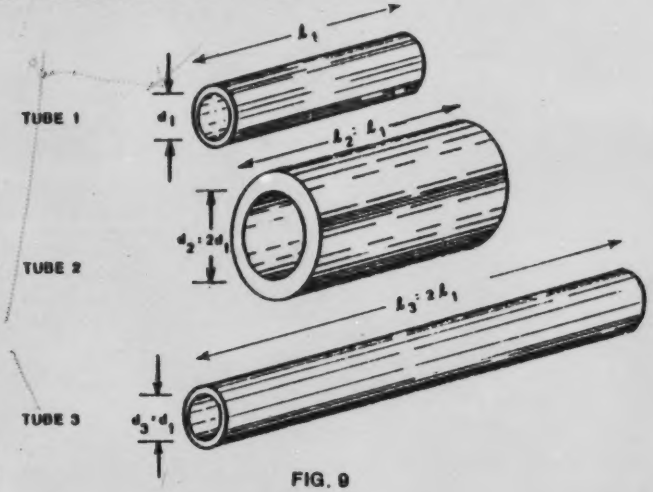


FIG. 9

PROCEDURE

1. Connect glass tube 1 to bottom outlet of large container, using short piece of rubber tubing as a connector, as shown in Figure 10. Place clamp on rubber tubing to prevent fluid flow.

2. Fill large reservoir, and measure liquid head (Δh); record this value in Data Table. Calculate pressure differential across pipe, and record in Data Table.

3. With tubing in horizontal position, open clamp, and allow the fluid to flow until quart container is filled. Record time required. Calculate and record fluid flow rate.

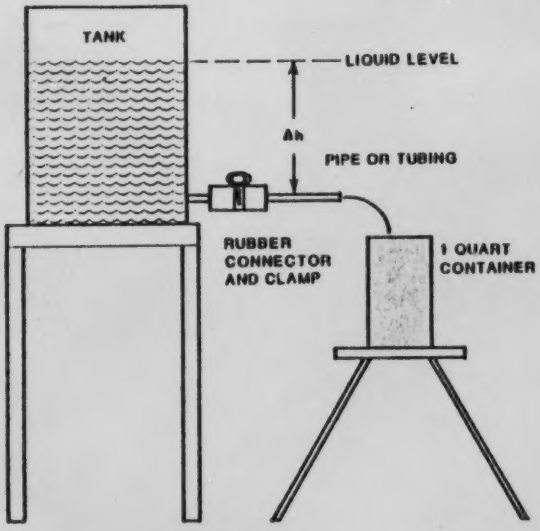


FIG. 10

4. Repeat steps 1-3 for other two pieces of tubing. Record all data in Data Table.

5. Repeat above procedure, using tube 3 and oil instead of water.

6. Draw the following graphs*:

   - Flow rate vs. tube diameter, using trials 1 and 2. Note that (d = 0, Q = 0) must be a point on the curve. (See Figure 5.)

   - Flow rate vs. tube length, using trials 1 and 3. Note that curve must approach axes asymptotically. (See Figure 6.)

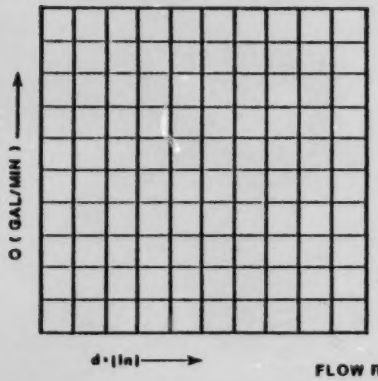
   - Flow rate vs. viscosity, using trials 3 and 4. Note that curve must approach axes asymptotically. (See Figure 7.)

7. State briefly the relationship of pipe diameter, pipe length, and viscosity to fluid flow rate; and support your statements with your experimental data.

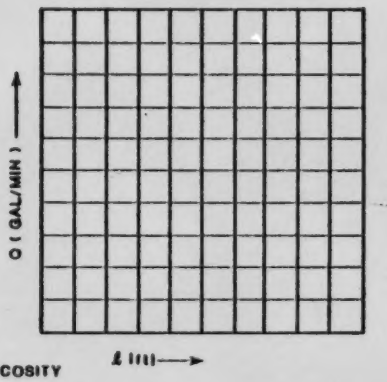
*Note: The graphs drawn in step 6 are based upon only two points. In general, one should plot graphs based upon more than two points; however, the trend predicted by only two points here will be seen to be in agreement with the plots shown in Figures 5, 6 and 7. Thus, in the interest of brevity, only two points will be "required" for the measurements plotted in step 6.

DATA TABLE								
Trial	Tube	Δh(ft)	Δp(lb/in^2)	ℓ(ft)	d(in)	t(s)	Q gal/min	η(cp)
1	1(ℓ,d)							H_2O
2	2(ℓ,2d)							H_2O
3	3(2ℓ,d)							H_2O
4	3(2ℓ,d)							oil

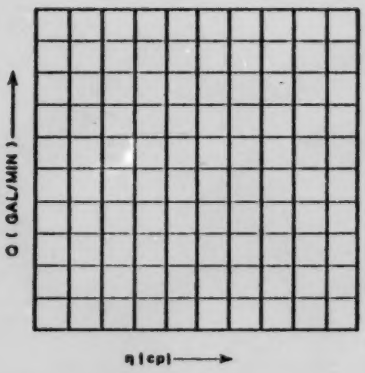
FLOW RATE VS. TUBE DIAMETER



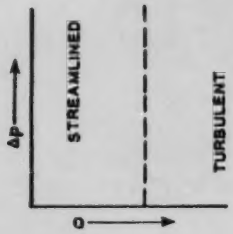
FLOW RATE VS. TUBE LENGTH



FLOW RATE VS. VISCOSITY



SELF CHECK



1. State how laminar fluid flow rate through a pipe changes as each of the following quantities is changed:

   (a) Pressure differential.
   (b) Pipe diameter.
   (c) Pipe length.
   (d) Fluid viscosity.

2. Draw graphs showing laminar fluid flow rate as a function of the following quantities:

   (a) Pressure differential.
   (b) Pipe diameter.
   (c) Pipe length.
   (d) Fluid viscosity.

3. Draw a typical curve of pressure differential versus fluid flow rate on the graph at the left.

4. Water (η = 1.0 cp) flows through a pipe 10 feet in length and 1/2 inch in diameter at a rate of 2 gal/min. Determine the pressure differential.

5. Oil (η = 1000 cp) flows through a pipe 8 feet long and 2 inches in diameter with a pressure differential of 18 lb/in^2. Determine the flow rate.

6. A fluid flows through a pipe at a rate of 32 gal/min. Determine the flow rate for each of the following conditions:

   (a) Double pipe length.
   (b) Double pipe diameter.
   (c) Decrease pressure differential by one-half.
   (d) Increase fluid viscosity to four times the original value.

7. Why is laminar flow preferred to turbulent flow in fluid power systems?

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Newton, Donald G. Fluid Power for Technicians. Englewood Cliffs, NJ: Prentice-Hall, Inc., 1971.

Technical Paper No. 410. "Flow of Fluids Through Valves, Fittings and Pipe." New York: Crane Engineering Division, 1969.

UTC

UNIFIED TECHNICAL CONCEPTS

MODULE 5F4

VALVES AND REGULATORS

FLUIDS

Technical Education Research Center - Southwest

TERC - SW

INTRODUCTION

Valves are devices used to control the flow of fluids and gases. The term "valve" is a general term and other words commonly used to mean the same thing are "cocks," "taps," and "faucets." There are many types of valves and an almost infinite number of applications in our industrial society. Regulators, more correctly identified as "pressure regulators," are devices that maintain a constant output pressure at different flow rates. This module discusses valves and regulators as variable fluid resistors. In the laboratory, the student will measure the resistance of valves and regulators.

PREREQUISITES

Student should have completed Concept Module 5-0, "Resistance," and Application Module 5F3, "Fluid Resistance in Pipes."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Define "fluid resistance," and discuss valves and regulators as variable fluid resistors.
- Explain the difference between valves and regulators in terms of function and design.
- Draw and label diagrams of the following types of valves:
    a. Screw-down stop valve.
    b. Plug cock.
    c. Gate valve.
- Draw and label a diagram of a gas-pressure regulator, and explain its operation.
- Given the appropriate equipment, take the necessary data and draw resistance curves for a valve and for a pressure regulator.

RESISTANCE IN FLUIDAL SYSTEMS

In Concept Module 5-0, "Resistance," the term "resistance" was defined as the ratio of a forcelike quantity to a rate. In fluidal systems, the fluidal resistance is the ratio of pressure to volume flow rate, which can be represented as the slope of a line, as shown in Figure 1. This figure depicts the resistance of a fixed-fluid resistance in which the pressure drop across the resistor increases as the flow rate increases.

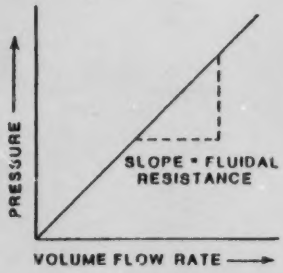


FIG. 1

In the fluid system, illustrated in Figure 2, resistance of the glass tubing is determined by the ratio of the pressure differential across the tubing to the volumetric flow rate through the tubing. If several pieces of tubing having equal lengths but different diameters are used, each will have its own characteristic curve, as shown in Figure 3. The tube with the greatest slope (pipe No. 1) has the greatest resistance. The vertical dashed line in Figure 3 indicates that for a given flow rate, a smaller-diameter pipe will have a greater pressure drop than a larger-diameter one. The horizontal line shows that at a constant pressure drop, a larger-diameter pipe (which has lower fluidal resistance) will allow a greater flow rate than a smaller one. Thus, both pressure drop and flow rate are related to the diameter of the pipe carrying the fluid.

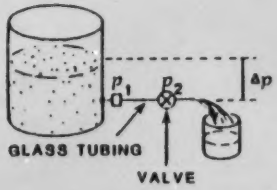


FIG. 2

In fluidal systems, control is accomplished by varying the size of an opening through which a fluid (either gas or liquid) passes. A valve is a device used to control flow rate; whereas, a regulator is a device used to control differential pressure. Both are variable fluid resistors in which resistance is changed by varying the area of an opening.

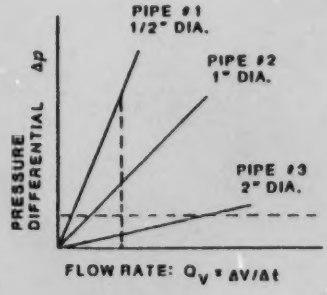


FIG. 3

VALVES

Ideally, a valve is a flow-control device that operates with a constant pressure drop. Enlargement of the opening in a valve reduces the resistance and increases the flow rate. When the valve is closed, no liquid flows (large resistance, equivalent to an open electrical circuit); and when the valve is completely open, the liquid flows at its maximum rate (small resistance, equivalent to a shorted electrical circuit).

The pressure drop across a valve actually is constant only if the valve is the only significant resistance in the system. In practical fluidal systems, other resistances have an effect upon the pressure drop across the valve.

Figure 4 illustrates a fluidal system containing a closed valve compared with a graph of pressure in the system as a function of distance along the pipes. When the valve is closed, the entire pressure differential between points A and B appears across the valve.

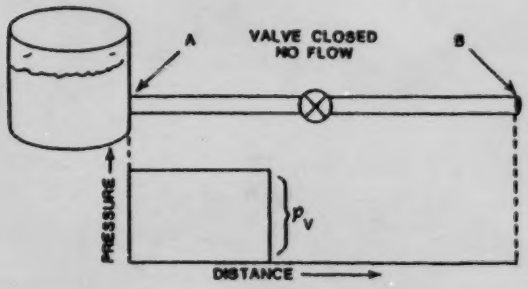


FIG. 4

Figure 5 depicts the same system with the valve open to allow fluid flow. In this case, there is a pressure drop along each of the pipes, and the differential pressure across the valve is much less than the total system pressure differential.

A valve has a fixed value of resistance for each of its settings, which means that both flow rate through the valve and differential pressure across the valve vary with the pressure applied to the system.

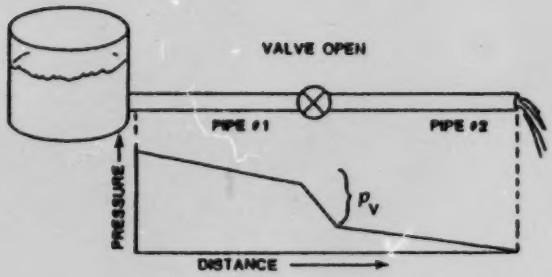


FIG. 5

TYPES OF VALVES

Perhaps the most familiar valve is the water tap, or faucet. This type of valve is technically closed as a screw down stop valve. Figure 6 consists of a schematic of this type of valve. Another type of valve commonly found in the laboratory and industrial setting is the plug cock (Figure 7). This valve is a simpler one, in which the fluid passage is a hole in a rotatable plug that has a slightly-tapered shape and is fitted into the body of the cock. The cock is opened or closed by rotation of the plug through an angle of 90°. Some degree of flow control is possible if the plug of the cock is set in an intermediate position. This type of valve is not used if accurate control of flow rate is desired.

A feature common to most manually-operated flow control valves is the stem, or screw spindle, surmounted by a hand-wheel. The fluid (gas or liquid) flows through an opening whose edge forms the valve seat. The ordinary domestic water tap illustrates the principle (Figure 6). The stem is connected to a disk usually provided with a replaceable sealing washer to make the actual contact with the seat and, thus, to stop the flow of water. To open the tap, the disk is raised by rotating the handwheel in the counterclockwise direction until the stem is screwed out of the valve body. Clockwise rotation brings the valve disk into contact with the seat and, thus, closes the tap. In some valves, the stem, instead of being provided with a disk, ends in a conical point inserted into a conical hole of the seat. The point closes into the hole when the stem is screwed home. This type of valve is known as a "needle valve" and is found in carburetors. The angle valve (Figure 8) is another variation of this concept.

Larger valves used for controlling the flow of liquids in pipelines, water mains, etc., often are of the kind illustrated in Figure 9.

This device is known as a "gate valve," or "sluice valve." In this valve, a wedge-shaped gate is actuated by a threaded stem and a handwheel. The gate bears against two seat faces to shut off the flow. The fluid flows through the gate valve in a straight

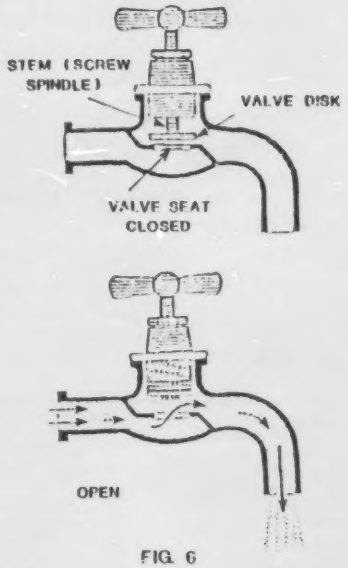


FIG. 6

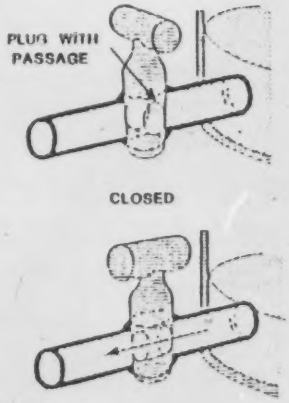


FIG. 7

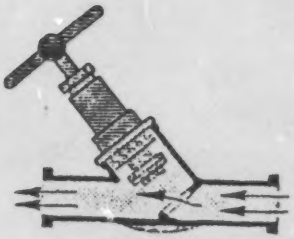


FIG. 8

line, causing the flow resistance to be minimized. The valve stem must be sealed at its point of entry into the valve body in order to prevent leakage of the fluid. The seal usually is formed by a "stuffing box" (Figure 10), which is a cylindrical recess filled with packing compressed by a sleeve, known as a "gland," to make a tight joint.

The material inserted in the stuffing box is called "packing." It may be a compressible material, such as hemp or asbestos. The pressure exerted by the gland keeps the packing tightly pressed against the valve stem.

REGULATORS

Valves have variable resistances, but the resistance of any particular valve is fixed for any setting of that valve. Unless the valve is adjusted, its resistance remains constant.

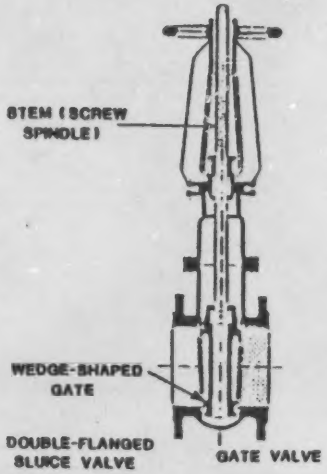


FIG. 9

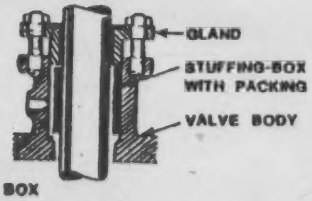


FIG. 10

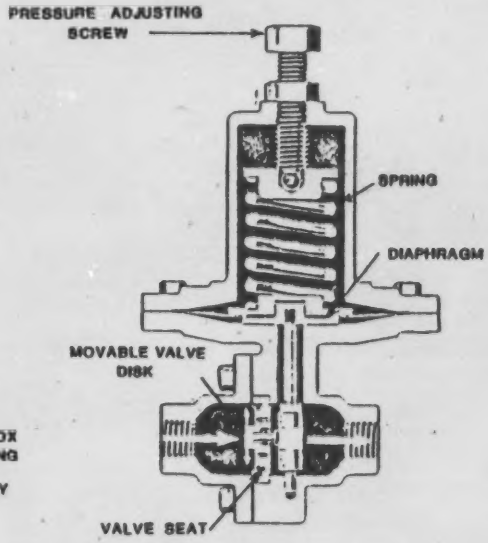


FIG. 11

A regulator is a variable fluidal resistor that responds to system changes to produce a constant pressure differential at varying flow rates. Figure 11 is a schematic of a typical gas-pressure regulator. The valve seat is a fixed disk containing a series of holes. A movable disk with a similar hole pattern slides vertically across the valve seat and is positioned by the motion of a diaphragm. The diaphragm is forced downward by spring tension from above and upward by the gas pressure down stream from the regulator. If down-stream pressure drops, the spring forces the diaphragm downward, opening the regulator to decrease resistance. This process allows a higher flow rate and brings steam pressure back to the desired level. If the down-stream pressure rises, it forces the diaphragm upward, increasing the resistance and reducing the flow. The operating pressure of the regulator is changed by adjustment of the spring tension on the diaphragm. Regulators of this type are used whenever a constant pressure is required in fluidal systems.

SUMMARY

Valves and regulators are variable fluidal resistors used to control flow rates and pressures in fluidal systems.

The resistance of a valve is adjustable, but is fixed for any valve setting. Thus, valves can be used to control flow rates, but not pressures; and flow rate through a valve changes as applied pressure changes.

Regulators are active devices whose fluidal resistance changes in response to changes in the system. A regulator senses the down-stream pressure and adjusts its resistance to maintain that pressure at a constant level.

DIFFERENTIAL PRESSURE OF VALVES AND REGULATORS

MATERIALS

Cylinder of nitrogen gas.
Pressure regulator for nitrogen cylinder.
Flow meter.
Pressure gage 0-20 psi.
Two valves.
Connecting tubing.

PROCEDURE

1. Connect equipment as in Figure 12. All gages indicate pressure above atmospheric. p_1 is input pressure to regulator. p_2 is output pressure of regulator. p_3 is input pressure of valve V_2.

   Output pressure of valve 2 is atmospheric pressure (0 psig).

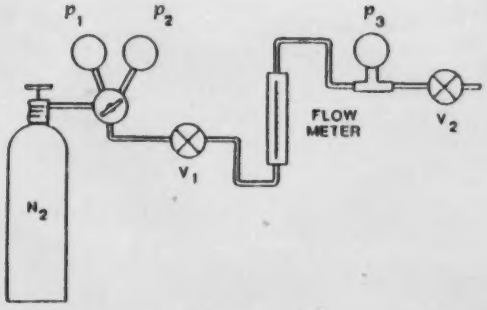


FIG. 12

2. Close V_1 and V_2. Turn regulator control counter-clockwise until no spring tension can be felt. If in doubt, unscrew regulator control until it can be removed.
3. Open nitrogen tank valve.
4. Set regulator for an output pressure of 10 psig on p_2.
5. Open V_1.
6. Adjust V_2 for several flow rates. Record p_1, p_2, and flow rate for five settings of V_2.
7. Draw a graph of pressure drop across the regulator versus flow rate.
8. Set V_2 to a slightly-open position.

9. Vary output pressure of regulator to produce valves of p_3 from 0 to 10 psig. Record p_3 and flow rate for five valves. (Output pressure of V_2 is 0 psig.)

10. Draw a graph of pressure drop across V_2 versus flow rate.

11. Close V_2.

12. Set regulator for output pressure of 10 psig.

13. Open V_2 to vary flow rate. Record p_3 and flow rate for five settings of V_2.

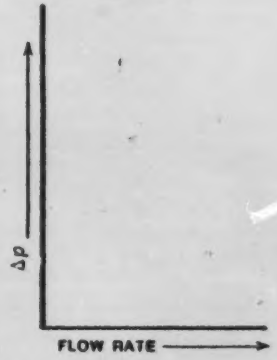
14. Draw a graph of pressure drop across V_2 versus flow rate as V_2 is opened.

15. Explain the shape of each curve drawn.

DATA TABLE

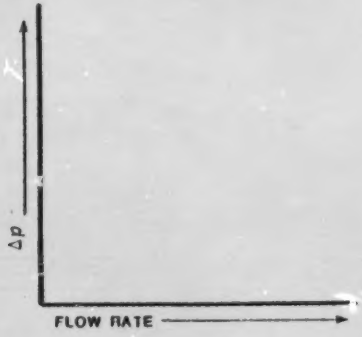
Differential pressure on regulator versus flow rate.

Δp ($p_1 - p_2$) psig	Flow rate



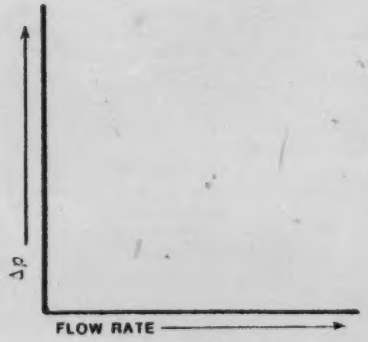
Differential pressure on valve versus flow rate at fixed valve resistance.

Δp (p_3) psig	Flow rate



Differential pressure on valve versus flow rate as valve resistance varies.

Δp (p_3) psig	Flow rate



SELF CHECK

1. Define "fluid resistance" with the use of a graph.

2. Draw graphs of differential pressure versus flow rate for each of the following:

   a. A valve at one specific setting.
   b. A pressure regulator at one specific setting.

3. Explain how the pressure drop across a valve in a fluidal system changes as the valve is opened to allow a greater flow rate.

4. Draw and label diagrams of the following valves:

   a. Gate valve.
   b. Screw-down stop valve.

5. Draw and label a diagram for a gas-pressure regulator, and explain how it functions.

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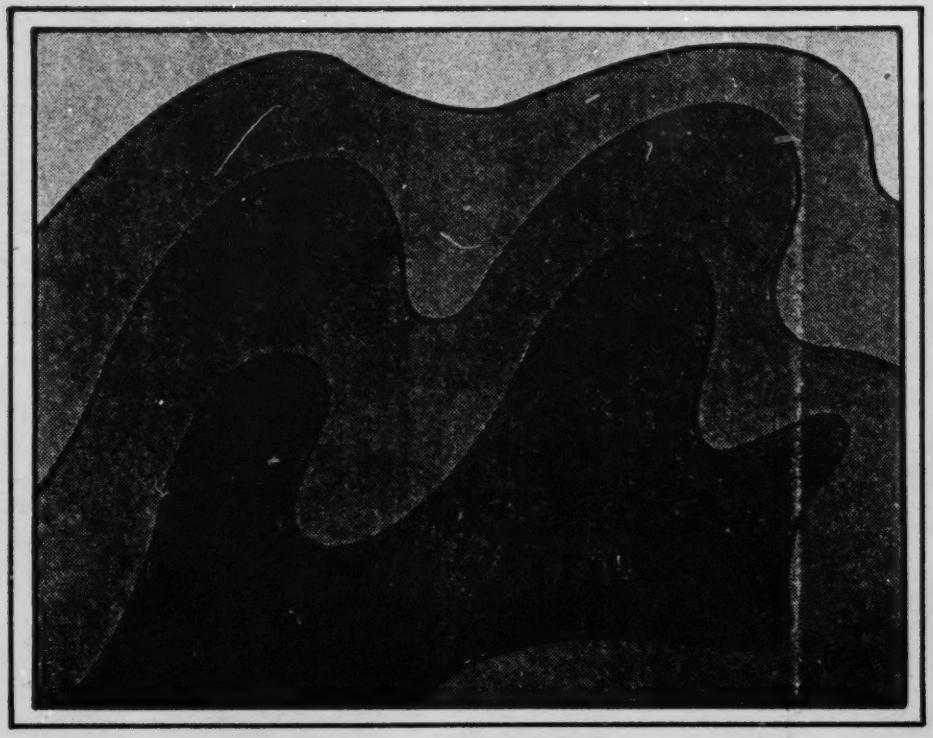
UNIFIED TECHNICAL CONCEPTS

MODULE 5 F 5

SHOCK ABSORBERS



FLUID APPLICATION OF RESISTANCE

Technical Education Research Center - Southwest

TERC - SW

INTRODUCTION

A shock absorber is a mechanical device providing resistance in a mechanical system. In most applications, this resistance is applied to reduce mechanical oscillations. In this module, the principles of operation and the construction details of several shock absorbers are presented. In the laboratory, the student will measure resistance of an automobile shock abosrber.

PREREQUISITES

Student should have completed Concept Module 5-0, "Resistance."

OBJECTIVES

To complete this module, the student should be able to:

- Draw and label the three major parts of a simple shock absorber and an automobile shock absorber.
- Explain in a short paragraph how the above shock absorber provides mechanical resistance.
- Explain in a short paragraph how a shock absorber works to provide different resistance for compression and decompression.
- Draw and label the four major parts of an automatic door closer.
- Given force, time and distance for compression and decompression of a shock absorber, calculate compression and decompression resistance of the shock absorber.
- Measure resistance of an automobile shock absorber for both compression and decompression, provided the appropriate equipment.

DISCUSSION

Figure 1 shows a liquid flowing through a pipe. As described in Concept Module 6-0, "Resistance," the resistance to fluid flow depends on viscosity of the liquid and diameter of the pipe. Resistance is greatest at the constriction where the diameter of the pipe is smallest. The shock absorber is an application of this principle.

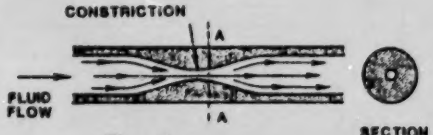


Fig. 1

Figure 2 shows a simple shock absorber. It consists of a piston that moves vertically in a cylinder filled with a viscous liquid. The piston contains a small-diameter hole through which the liquid may flow. On the compression (downward) stroke, pressure increases below the piston and liquid flows upward through the hole. On the decompression (upward) stroke, pressure is decreased below the piston and liquid flows downward through the hole. Resistance provided to the up and down motion of the piston depends on viscosity of the liquid and size of the hole in the piston.

The shock absorber in Figure 2 offers the same resistance for both up and downward movement of the piston (compression and decompression). In many applications, it is desirable to provide two different resistances for the up and down movement. A simple method of accomplishing this is shown in Figure 3. An additional hole in the piston has been equipped with a flap valve. On the compression (down) stroke, fluid pressure from below opens the valve allowing flow through two holes, resulting in less resistance to fluid flow and a lower resistance to the downward motion of the piston. During the decompression (up) stroke, fluid pressure is greatest above the piston, holding the flap valve closed. The same volume of fluid must now flow only through the smaller hole, providing greater resistance to upward motion of the piston.

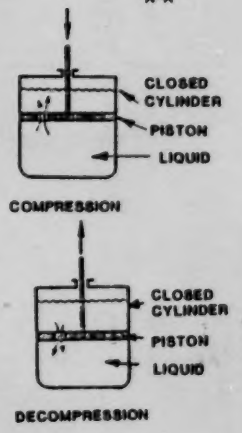


Fig. 2

Perhaps the most familiar shock absorber is the telescopic type commonly incorporated in automobile suspension systems. Figure 4 shows construction details and resistance operation of this type of shock absorber. Essential elements are a piston with two piston flap valves, a cylinder filled with oil, a bottom valve, and a fluid reservoir surrounding the cylinder. A more detailed view of the bottom valve is shown in Figure 5.

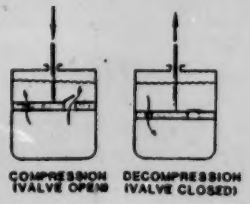


Fig. 3

During the compression stroke, the piston moves downward in the cylinder and oil flows through one of the piston flap valves to the space above the piston. The other piston flap valve is held closed by the greater fluid pressure below the piston. As

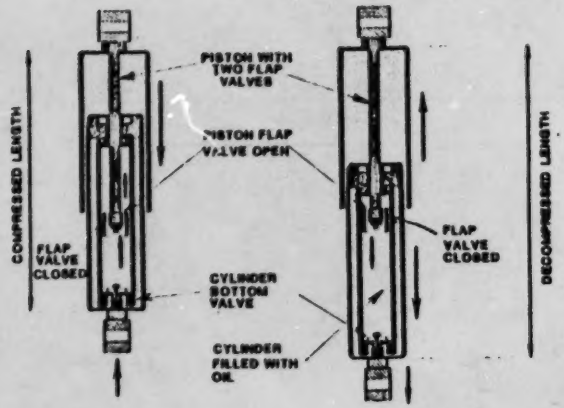


Fig. 4

the piston rod moves into the cylinder, the total volume of oil in the cylinder must be reduced by the volume of the rod. Pressure in the lower half of the cylinder opens the bottom valve, and oil flows through the large center opening into the fluid reservoir.

During decompression, the piston moves upward in the cylinder. The piston flap valve that was open during compression is held closed by the greater pressure above the piston, and the other piston flap valve is forced open to allow a downward flow of oil. As the piston rod is removed from the cylinder, oil flows back into the cylinder through the cylinder bottom valve from the reservoir. In this case the bottom valve is held closed by the greater pressure in the reservoir and the oil flows only through the small outer openings of the valve, resulting in a much greater resistance than during compression.

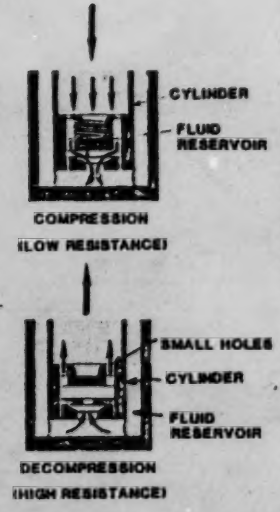


Fig. 5

Figure 6 shows an automobile suspension with coil springs and telescopic shock absorbers. When the wheel encounters the bump, the shock absorber is compressed and offers little resistance. Resistance to an upward motion of the wheel is due primarily to compression of the spring. After the bump is passed, the spring forces the wheel downward again. On the downward (decompression) stroke, the higher resistance of the shock absorber reduces or damps the motion of the spring to prevent oscillations. Cars with bad shock absorbers "bounce" because decompression resistance is no longer great enough to effectively damp out the oscillations.

Thus far, we have considered shock absorbers that employ noncompressible fluids (liquid) such as oil. Figure 7 shows a shock absorber that uses air as a working fluid. This device is an automatic door closer, consisting of a piston with a flap valve, a cylinder with a small opening in the end and a coil spring. When the door is opened (decompression), the coil spring is compressed and air enters the cylinder through the valve in the piston. When the door is released (compression), the coil

spring releases its stored energy and forces the piston inward to close the door. As the piston moves inward, the flap valve closes and the air in the cylinder is compressed. The small hole in the end of the cylinder provides high resistance to air flow out of the cylinder. This causes the door to close slowly.

Resistance of a shock absorber is given in Equation 1 as the ratio of a forcelike quantity to a ratelike quantity:

$$\text{Resistance of snock absorber} = \frac{\text{applied force}}{\text{velocity of piston}}.$$

$$\text{In symbols:} \quad R = \frac{F}{V}. \qquad (1)$$

Example A shows use of this equation in solving a problem.

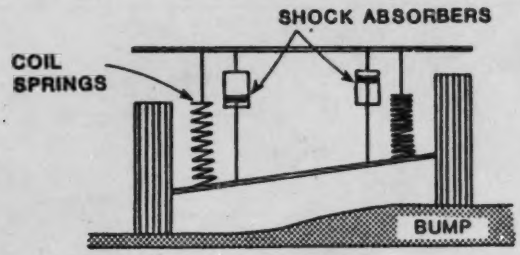


Fig. 6

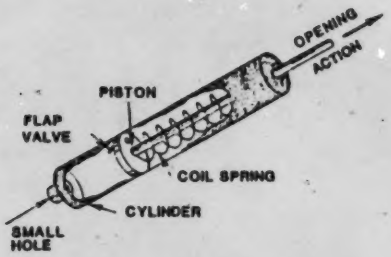


Fig. 7

EXAMPLE A: CALCULATION OF COMPRESSION AND DECOMPRESSION RESISTANCE

Given: With a compression force of 15 lb, the piston of a shock absorber moved 3 inches in 4 seconds. With a decompression force of 15 lb, a 3-inch motion required 12 seconds.

Find: Compression resistance and decompression resistance of the shock absorber. (Subscript c is for compression and subscript d is for decompression.)

Solution:

Compression velocity:
$$V_c = \frac{d_c}{t_c}$$
$$= \frac{3 \text{ in}}{4 \text{ s}}$$
$$V_c = 0.75 \text{ in/s}.$$

Compression resistance: (From Equation 1)
$$R_c = \frac{F_c}{V_c}$$
$$= \frac{15 \text{ lb}}{0.75 \text{ in/s}}$$
$$R_c = 20 \frac{\text{lb}}{\text{in/s}}.$$

Decompression velocity:
$$V_d = \frac{d_d}{t_d}$$
$$= \frac{3 \text{ in}}{12 \text{ s}}$$
$$V_d = 0.25 \text{ in/s}.$$

Decompression resistance: (From Equation 1)
$$R_d = \frac{F_d}{V_d}$$
$$= \frac{15 \text{ lb}}{0.25 \text{ in/s}}$$
$$R_d = 60 \frac{\text{lb}}{\text{in/s}}.$$

Thus decompression resistance is three times as high as compression resistance.

MATERIALS

Automobile shock absorber.
Sandbag (approximately 25 lb).
Scale in inches.
Lab timer accurate to 0.1 s.
Heavy string or wire to hold 30 lb.
Mounts for shock absorber (Figures 8 and 9).

PROCEDURE

1. Weigh sandbag; record weight in data table.
2. Compress shock absorber; make a reference mark at one end.
3. Mount shock absorber as shown in Figure 8; record initial height of reference mark above table. Attach sandbag; start timer. When downward motion of sandbag stops, stop timer. Make sure support is high enough to prevent sandbag from hitting table before it is fully extended. Record elapsed time and final height of reference mark.
4. Mount shock absorber as shown in Figure 9. Shock absorber must be firmly attached to a sturdy base or table top so it is held in a vertical position. Weight platform must be large enough to support sandbag and must also be firmly attached to shock absorber. Exact mounting technique will depend on shock absorber used.
5. Pull shock absorber out to its fullest extension.
6. Measure and record height of reference mark. Place sandbag on platform; release it; start timer. (Do not drop sandbag onto weight platform.)
7. When downward motion of sandbag stops, stop timer. Record elapsed

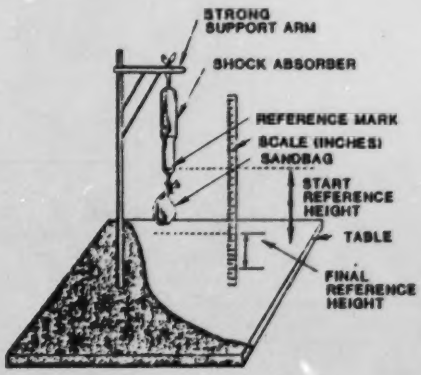


Fig. 8

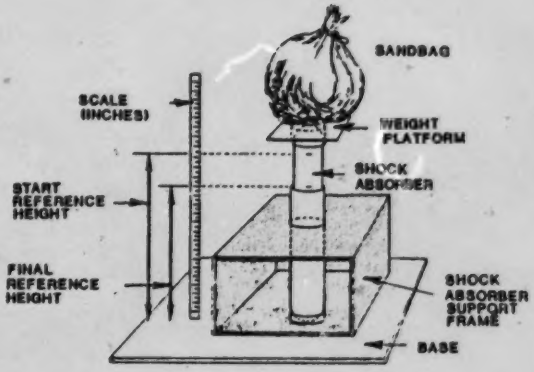


Fig. 9

time and final height of weight platform.

8. Complete data table.

DATA TABLE							
	Weight Of Sandbag (lb) (force)	Beginning Height (in)	Final Height (in)	Distance Traveled (in)	Elapsed Time (s)	Velocity (in/s) (V)	Resistance $R = \frac{\text{force}}{V}$ $(\frac{\text{lb}}{\text{in/s}})$
Decompression							
Compression							

SELF CHECK

1. Draw and label a simple shock absorber.
2. Explain in a short paragraph how shock absorbers provide mechanical resistance.
3. Draw and label an automobile shock.
4. Explain in a short paragraph how the automobile shock absorber functions to provide different resistance for compression and decompression.
5. Draw and label an automatic door closer.
6. A 20-lb force compresses a shock absorber 2.5 inches in 1.6 s. The same shock absorber is decompressed 3.4 inches in 2.6 s for a force 45 lb. Calculate compression and decompression resistances of the shock absorber.

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UNIFIED TECHNICAL CONCEPTS

MODULE 5 F 6

DRAG - RESISTANCE TO MOTION THROUGH FLUIDS

FLUID APPLICATION OF RESISTANCE

Technical Education Research Center - Southwest

TERC - SW

INTRODUCTION

When an object moves through a fluid or when a fluid moves around an object, a force acts to impede the motion. In this module, the student will become familiar with the properties of this fluid drag force and will learn how to calculate its magnitude. The student also will learn how to calculate the terminal velocity of an object moving through a fluid.

In the laboratory, the student will construct a device with which to measure the drag force exerted on a sphere by a stream of gas and will calculate the sphere's drag resistance.

PREREQUISITES

Student should have completed Concept Module 5-0, "Resistance"; and Application Modules 5F1, "Laminar and Turbulent Flow," and 5F2, "Viscosity."

OBJECTIVES

Upon completion of this module, the student should be able to:

- List three factors that determine the magnitude of the fluid drag force.
- Define the following in words and symbols:

  Drag resistance.
  Terminal velocity.

- Given two of the three quantities — fluid drag force, drag coefficient, and relative fluid velocity — calculate the third; and characterize the flow as laminar or turbulent.
- Given two of the three quantities — drag resistance, drag force, and relative fluid velocity — calculate the third.
- Given two of the three quantities — drag forces, propelling force, and drag coefficient — calculate the terminal velocity of an object moving through the fluid.

- Given the appropriate equipment, measure the drag force exerted on a sphere by a gas stream at different speeds, and calculate its drag resistance.

DRAG RESISTANCE

The fluid drag force that impedes the motion of an object through a fluid (or the motion of a fluid around an object) depends upon three variables: (1) the relative speed of the fluid and object, (2) the shape of the object, and (3) the viscosity of the fluid. The drag force on an object moving through a fluid increases as the relative speed of object and fluid increases.

The drag force on an object moving through a fluid (regardless of which one actually is moving) is due to the expenditure of energy required to separate the fluid. Thus, as the object moves through the fluid, work is performed to overcome the drag force exerted by the fluid.

A quantity often used to characterize the affect of fluid drag on an object is the drag resistance, as given by Equation 1.

$$R_D = \frac{F_D}{v} \qquad (1)$$

where

R_D = drag resistance.
F_D = magnitude of drag force.
v = relative fluid velocity.

The drag resistance is a scalar quantity that has units of force divided by speed. In the SI system, the units of drag resistance are N/(m/s); in the English system they are lb/(ft/s).

The difference between drag resistance and flow resistance is an important one and is defined in Concept Module 5-0, "Resistance." Flow resistance is defined in Equation 2.

$$R_F = \frac{\Delta p}{v_F} \qquad (2)$$

where

R_F = flow resistance.
Δp = pressure difference.
v_F = flow velocity.

Flow resistance is concerned with the resistance to fluid flow through a pipe, for example. Notice that flow resistance in SI units is expressed as $(N/m^2)/(m/s)$. In each case, however, the resistance is expressed as the ratio of a force like quantity divided by a rate like quantity (velocity). Pressure difference is chosen for the force like quantity in Equation 2 because it

is measured easily for fluid flowing in a pipe. For the case of fluid moving around an object, however, the force of the object is the forcelike quantity measured most easily; hence, the use of drag force in Equation 1.

LAMINAR FLOW

The fluid is easily separated (and the drag force is smallest) when the flow around the object is laminar. (Refer to Module 5F1, "Laminar and Turbulent Flow.") Figure 1 illustrates laminar flow of fluid around a wing-shaped object (airplane wing or hydrofoil). The fluid separates smoothly and flows in streamlines around the wing. For laminar flow, energy is expended only to separate the fluid and to redirect its flow around the object. One property of laminar flow is that the flow returns to its original flow pattern after the object has been passed. This property is observable in Figure 1.

FIG. 1

In order to exhibit laminar flow, the fluid in a flow system must not be forced to change direction too rapidly. This goal may be accomplished in several ways, but the simplest method is to ensure that the fluid flows slowly and smoothly around the object. In general, any flow can be made laminar if the flow velocity relative to the object is made small enough. In this way, sufficient time is allowed for the fluid to conform its flow smoothly to the shape of the object.

A second method of achieving laminar flow is to change the shape of the object to allow for smooth separation of the fluid and streamlined flow around the object. This method is called "streamlining" and is of great practical importance in designing low-drag systems. Almost all systems designed to operate with low drag at high speeds utilize streamlining. Automobiles, boats, fast trains, and aircraft are carefully designed and are tested by application of streamlining and are to minimize drag. Probably the best example of a naturally-streamlined object is the raindrop. Its shape allows air to flow smoothly around it at maximum speed, thus minimizing the drag at that speed; the flow is laminar.

For laminar flow, the magnitude of the drag force on an object moving through a fluid is given by Equation 3.

$$F_D = c_D v_F \qquad (3)$$

where

c_D = a constant – the "drag coefficient," determined by shape of object and viscosity of fluid.

Example A illustrates the use of Equations 2 and 3 in solving a problem. It also illustrates an interesting property of laminar flow; namely, that the drag coefficient and the drag resistance are equal and constant. If the drag force is plotted as a function of velocity in the liminar flow regime, the result is a straight line (Figure 2), as one certainly should expect from an inspection of Equation 3.

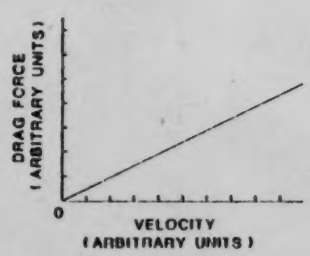
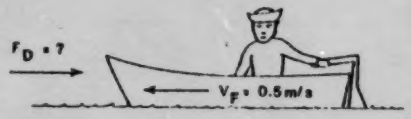


FIG. 2

EXAMPLE A

Given: A boat drifts through calm water at the rate of 0.5 m/s. The drag coefficient is 3 N/(m/s). Assume laminar flow.



C_D = 3N/(m/s)

Find: (a) The drag force exerted on the boat.
(b) The drag resistance.

Solution: (a) $F_D = c_D v_F$

$= (3 \frac{N}{m/s})(0.5\ m/s)$

$F_D = 1.5\ N$

(b) $R_D = \frac{F_D}{v_F}$

$= \frac{1.5\ N}{0.5\ m/s}$

$R_D = 3 \frac{N}{m/s}$

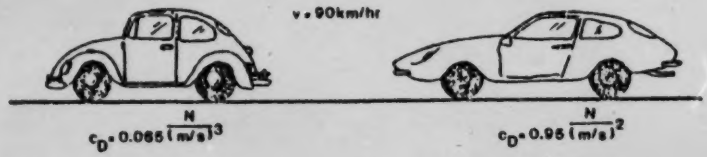
The importance of streamlining in reducing drag resistance is illustrated in Example B.

EXAMPLE 8

Given: The equations for the drag force for two automobiles traveling at 90 km/hr are given below:

Volkswagen: $F_D = c_D v_F^3$; $c_D = 0.065 \frac{N}{(m/s)^3}$

Jaguar: $F_D = c_D v_F^2$; $c_D = 0.95 \frac{N}{(m/s)^2}$



Find: The drag force upon (a) the Volkswagen and upon (b) the Jaguar.

Solution: Convert the speed to m/s.

$$(90 \frac{km}{hr})(\frac{1000\ m}{1\ km})(\frac{1\ hr}{60\ min})(\frac{1\ min}{60\ s}) = 25\ m/s$$

(a) Volkswagen: $F_D = c_D v_F^3$

$$= (0.065 \frac{N}{(m/s)^3})(25\ m/s)^3$$

$$F_D = 1016\ N$$

(b) Jaguar: $F_D = c_D v_F^2$

$$= (0.95 \frac{N}{(m/s)^2})(25\ m/s)^2$$

$$F_D = 594\ N$$

Notice that the well-streamlined Jaguar experiences a significantly smaller drag force than the poorly-streamlined Volkswagen.

TURBULENT FLOW

As an object moves faster and faster through a fluid, laminar flow becomes more difficult to maintain, and turbulence sets in. Figure 3a depicts the onset of turbulence in the fluid as manifested by the creation of small regions of swirling fluid called "vortices." Each vortex is similar to a "small tornado" in the fluid. The creation of the vortex requires energy; therefore, for turbulent flow

around an object, energy is expended both to separate the fluid and to create vortices.

The number of vortices — and, thus, the turbulence — increases with the relative speed of fluid to object. Figure 3b illustrates extremely turbulent flow around a very fast-moving wing.

Once created, vortices die away very slowly, persisting long after the object has passed. Large, fast-moving aircraft create considerable turbulence as they pass through the air. Powerful vortices that can buffet a small aircraft severely may continue to exist as far as a mile behind a commercial jet. Thus, one property of turbulent flow is that the fluid remains disturbed for a considerable time after the passage of the object.

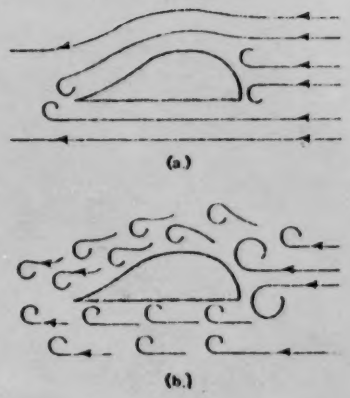


FIG. 3

For the simplest case of turbulent flow, the drag force is given by Equation 4.

$$F_D = c_D v_F^2 \qquad (4)$$

The constant c_D still is called the drag coefficient; it depends upon the object shape and the fluid viscosity. The drag coefficient, however, is not the same for laminar and turbulent flow. Indeed, for the flow described by Equation 4, the units of c_D are force divided by velocity squared. A combination of Equations 1 and 5 yields an expression for the drag resistance in the form of Equation 5.

$$R_D = \frac{F_D}{v_F} = \frac{c_D v_F^2}{v_F} = c_D v_F \qquad (5)$$

In general, as speed and turbulence increase, the power of v_F in Equation 4 also may increase, as indicated by Equations 6 and 7.

$$\left.\begin{aligned} F_D &= c_D v_F^n \qquad (6) \\ R_D &= \frac{F_D}{v_F} = \frac{c_D v_F^n}{v_F} = c_D v_F^{n-1} \qquad (7) \end{aligned}\right\} \quad n = 2,3,4....$$

Notice that for turbulent flow, the drag resistance always depends upon the speed. Figure 4 is a graph of drag force versus velocity

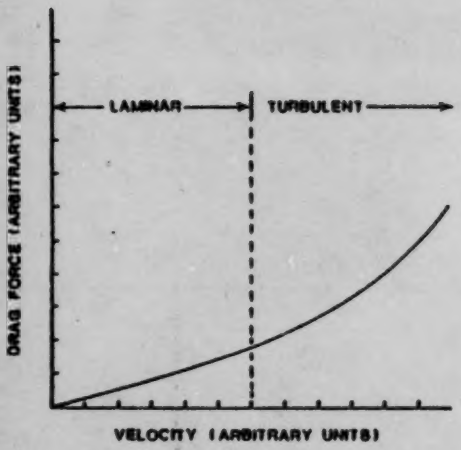


FIG. 4

of an object in both the laminar and turbulent flow regimes. The graph is a straight line only in the laminar region; it is a curved line after the velocity increases sufficiently to cause turbulence.

TERMINAL VELOCITY

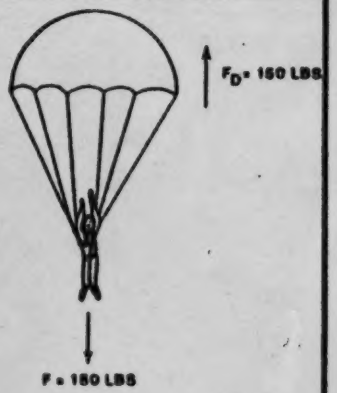
Whenever an object is propelled through a fluid by a constant force, the drag force acts to oppose the motion. As the object accelerates and its speed increases, the drag force also increases until, ultimately, it is equal in magnitude to the propelling force. The object then is in equilibrium and can accelerate no longer. It then continues to travel at the highest speed it attained through the fluid — at the so-called "terminal velocity." The terminal velocity is the maximum speed with which an object can travel through a fluid. It corresponds to the speed of the object when the propelling force is equal to the drag force. Example C illustrates the concept of terminal velocity in a problem that involves a skydiver.

EXAMPLE C

Given: A 150-lb skydiver opens his parachute. Its drag coefficient is 10 $\frac{\text{lb}}{\text{ft/s}}$ and the air flow around the parachute is laminar.

Find: His terminal velocity v_T.

Solution: The skydiver is being propelled downward by his weight. Hence, to achieve equilibrium, the drag force must equal his weight.



$F_D = 150$ lbs

$c_D v_F = 150$ lbs ($F_D = c_D v_F$ for laminar flow.)

$(10 \frac{\text{lb}}{\text{ft/s}})\ v_F = 150$ lbs

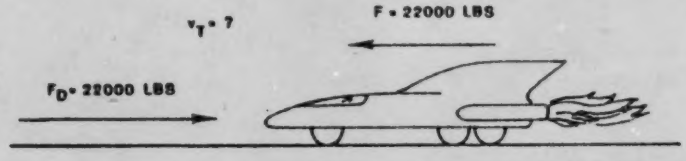
$$v_F = \frac{150 \text{ lbs}}{10 \frac{\text{lb}}{\text{ft/s}}} = 15 \text{ ft/s}$$

The terminal velocity of the skydiver is 15 ft/s (about 10 mi/hr).

The parachute is a device that depends upon the concept of terminal velocity for its proper operation. Many devices, however, have their performance hampered by the existence of a terminal velocity; for instance, any device designed to move rapidly through a fluid is limited in speed ultimately by the terminal velocity. Consider, for instance, the problem of the rocket car in Example D.

EXAMPLE D

Given: A rocket-powered automobile develops a thrust (propelling force) of 22000 lbs. At its maximum speed, it operates in the turbulent flow regime where $F_D = c_D v_F^3$ and $c_D = 2 \times 10^{-5} \frac{\text{lb}}{(\text{ft/s})^3}$.



Find: Its terminal velocity (neglecting internal friction).

Solution: Propelling force = drag force

$$22000 \text{ lb} = c_D v_F^3$$

$$22000 \text{ lb} = (2 \times 10^{-5} \frac{\text{lb}}{(\text{ft/s})^3}) v^3$$

$$v_T^3 = \frac{22000 \text{ lb}}{2 \times 10^{-5} \text{ lb}/(\text{ft/s})^3} = 11 \times 10^8 \text{ ft}^3/\text{s}^3$$

$$v_T = \sqrt[3]{11 \times 10^8 \text{ ft/s}^3} = 1032 \text{ ft/s}$$

$$= (1032 \text{ ft/s})(\frac{1 \text{ mi}}{5280 \text{ ft}})(\frac{60 \text{ s}}{1 \text{ min}})(\frac{60 \text{ min}}{1 \text{ hr}})$$

$$v_T = 704 \text{ mi/hr}$$

The terminal velocity of the car (neglecting internal friction) is 704 mi/hr.

SUMMARY

Fluid drag force depends upon three variables — (1) relative speed of the fluid and of the object, (2) shape of the object, and (3) viscosity of the fluid. "Laminar flow" is the smooth flow of fluid; whereas, "turbulent flow," as the name implies, is the rough, resisted flow usually exhibited by fluids moving at high velocities. If objects are "streamlined" in design, they move through fluids with less turbulence. If a free body is moving in a resisting medium and if it is acted upon by a constant force, it accelerates until a certain "terminal velocity" is attained, after which the velocity remains constant.

DRAG FORCE AND DRAG RESISTANCE

MATERIALS

Regulated source of compressed gas (air or nitrogen).
Transparent tube (4 cm inside diameter x 50 cm long).
Styrofoam ball (approximately 1 cm diameter).
2 lengths of hose (¼" inside diameter).
2 glass tubes (¼" outside diameter).
Trough.
Large test tube or graduate (at least 50 cm).
Glass slide.
Support stands and clamps.
Paperclip.
2 lightweight rubber bands.
Stopwatch.
Centimeter scale.
Duct Tape.
Masking tape.
Hooked masses.

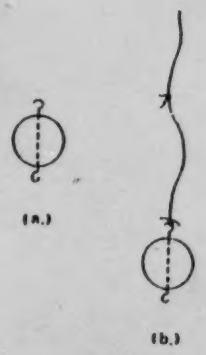


FIG. 5

PROCEDURE

1. Straighten paperclip, and fashion a small hook on one end. Push clip through styrofoam ball, and fashion another hook on the other end (Figure 5a).

2. Sever each rubber band, and tie them together to form a long elastic "string." Tie one end to hook on ball (Figure 5b).

3. Push one end of each ¼" hose over a glass tube. Tape free end of rubber band to one of glass tubes. (See Figure 6.)

4. Measure diameter d_1 of the large tube, and record its value in Data Table. Mate a glass tube to each end of large tube, using duct tape to ensure a relatively leak-tight seal. Use a support stand to hold assembly in a vertical orientation. Run a strip of masking tape down side of tube. After completing this step the assembly

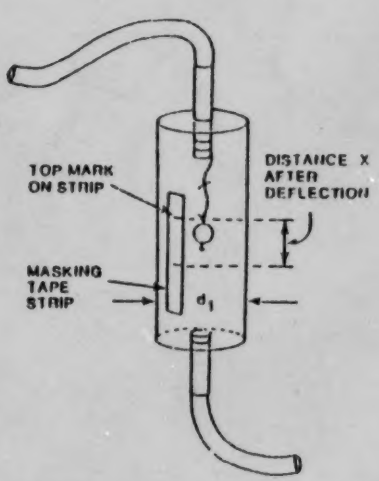
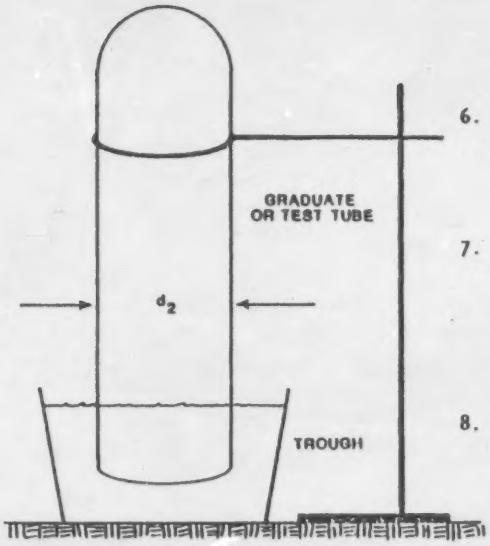


FIG. 6

should look like that illustrated in Figure 6.

5. Partially fill trough with water. Measure and record diamter d_2 of graduate or test tube. Completely fill test tube, press glass slide against open end, and invert tube. Place end with glass slide below water level in trough, and remove slide. Hold test tube in this position with a support stand. The test tube should remain full of water. (See Figure 7.) Place two marks a distance ℓ = 20 cm apart along the cylindrical portion of test tube.



6. To complete assembly of this device, attach free end of upper (inlet) hose to gas source, and place end of lower (outlet) hose in trough. (See Figure 8.)

7. Mark position of top hook on masking-tape strip. Start gas flow, and adjust it so that the ball is deflected a small, but constant, distance below its initial position. Mark new position of top hook on masking tape.

8. With gas still flowing at same rate, slide outlet hose under test tube so that all escaping gas is collected. When water level in test tube reaches top mark, start stopwatch; and mark time until it reaches lower mark, 20 cm below top mark. Record this time t in Data Table.

9. Stop gas flow, and measure deflection distance x of styrofoam ball between two marks. Record this distance in Data Table.

10. Refill test tube, and repeat Steps 7-9 for at least four more deflections.

11. Calculate flow rate (in cm^3/s) corresponding in each deflection from the following relation:

$$Q_V = \frac{\frac{1}{4}\pi d_2^{\,2} \times 20 \text{ cm}}{\Delta t}$$

where

Q_V = volume flow rate.

$\frac{1}{4}\pi d_2^{\,2} \times 20$ cm = volume of water displaced.

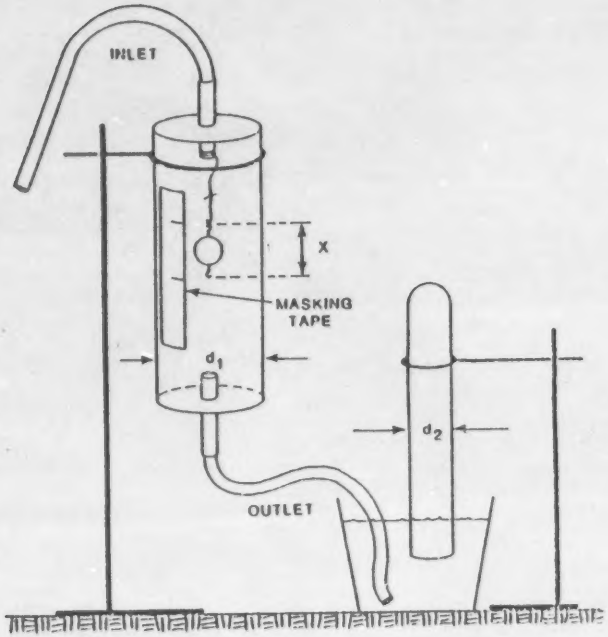


FIG. 8

Δt = elapsed time of flow, corresponding to 20 cm fall of level of water in graduate.

12. Calculate gas velocity through large tube for each deflection from this relation:

$$v = \frac{Q_V}{\frac{1}{4}\pi d_2^2}$$

where
$\frac{1}{4}\pi d_2^2$ = cross-sectional area of large tube.

13. Remove ball and rubber bands from tube, and rehang them from a support stand. Hang sufficient hooked masses from lower hook to achieve a deflection of 5 cm. Record this mass m in Data Table. Calculate spring constant k of the rubber band from the following:

$$k = \frac{m \times 980\ cm/s^2}{5\ cm}$$

14. Since the ball is in static equilibrium during the experiment, drag force acting upon it is equal in magnitude to restoring force of rubber bands. The drag force, therefore, can be calculated from this equation for a given deflection x:

$$F_D = kx$$

Calculate drag force acting upon ball for each deflection.

15. On the graph provided, plot drag force F_D (in dynes, where 1 dyne = 10^{-5} newtons) on vertical axis versus gas velocity v (in cm/s). Draw best straight line through these points. (Note: This line should pass through the origin.)

16. Choose a point on line near its end. Calculate the drag resistance of styrofoam sphere from coordinates of this point, using Equation 1.

DATA TABLE

d_1 = _____ cm m = _____ g

d_2 = _____ cm $k = \frac{m \times 980\ cm/s^2}{5\ cm}$ = _____ $\frac{dynes}{cm}$

ℓ = 20 cm $R_D = \frac{F_D}{v_F}$ = _____ dynes/(cm/s)

Deflection x (in cm)					
Time t (in s)					
Flow Rate Q_V (in cm^3/s) $Q_V = \frac{\frac{1}{4}\pi\ell d_2^2}{t}$					
Gas Velocity v_F (in cm/s) $v_F = \frac{Q_V}{\frac{1}{4}\pi d_1^2}$					
Drag Force F_D (in dynes) $F_D = kx$					

SELF CHECK

1. List three factors that determine the magnitude of fluid drag force.

2. Define the following terms:

   Drag resistance.

   Terminal velocity.

3. A falling skydiver has a drag coefficient of $c_D = 5.8 \times 10^{-1} \frac{lb}{(ft/s)^2}$ and falls at the rate of 100 mi/hr before opening his parachute. Assume turbulent flow where $c_D v_F^2$. Find the following values for the time immediately before his parachute is opened:

   a. The drag force exerted on the skydiver.
   b. His drag resistance.

4. The propellers of a fast-moving nuclear submarine provide a thrust of 100,000 lb. The terminal velocity of the submarine is 50 mi/hr when submerged. Assume that the drag force is given by $F_D = c_D v_F^3$.

   a. The drag coefficient of the submarine.
   b. The drag resistance of the submarine at its terminal velocity.

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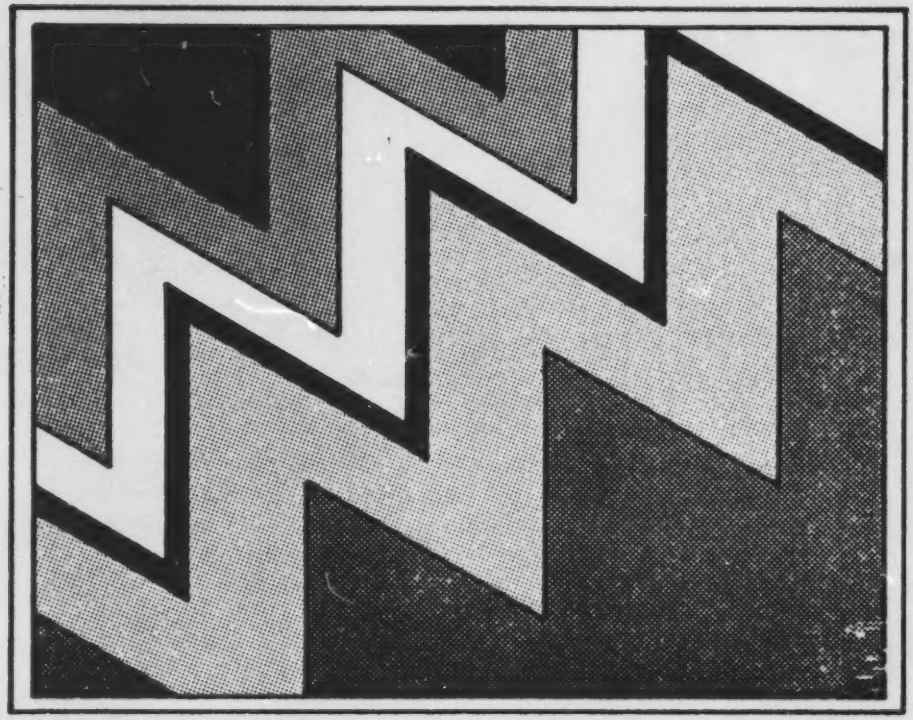
UNIFIED TECHNICAL CONCEPTS

MODULE 5 E 7

RESISTANCE OF GAS LASER TUBES



ELECTRICAL APPLICATION OF RESISTANCE

Technical Education Research Center - Southwest

TERC - SW

INTRODUCTION

During the relatively brief time since the construction of the first laser, modern technology has found a myriad of applications for lasers of many types. These applications embrace many different fields: electronics, manufacturing, communications, surveying, medicine energy and many others.

In this module, the student will become familiar with the electrical characteristics of one class of lasers — the gas laser. These principles will be applied to delineate the general requirements for a gas-laser power supply.

In the laboratory, the student will measure the electrical properties of a gas discharge tube.

PREREQUISITES

Student should have completed Concept Module 5-0, "Resistance," and Application Module 5E1, "Ohm's Law."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Define the following terms:

  Ion.
  Breakdown voltage.
  V-I characteristic curve.
  Sustaining voltage.

- State two ways in which neutral atoms in a gas laser tube can be ionized. Briefly explain each process.

- Describe the behavior of the voltage across a laser tube relative to the current through it for a tube operating in the negative resistance region.

- List the three elements of a gas-laser power supply, and briefly explain the function of each.
- Given the running supply voltage, the desired operating current, and the V-I characteristic of the tube, calculate the necessary ballast resistance.
- Given the V-I characteristic of a laser tube, determine the values of the breakdown voltage and of the sustaining voltage; and label the negative resistance region.
- Given the appropriate equipment, collect the data required to plot the V-I characteristic of a neon bulb.

DISCUSSION

Figure 1 depicts a gas-filled tube; it is similar to an ordinary gas laser tube. A voltage is maintained across the tube by connecting each electrode to one of the terminals of a battery or power supply. The electrode connected to the positive terminal is called the "anode." The electrode connected to the negative terminal is termed the "cathode."

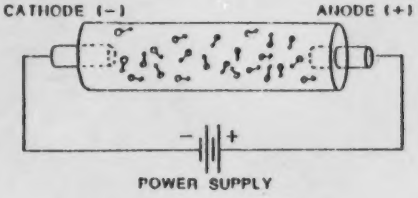


FIG. 1

Under ordinary circumstances, the atoms of the gas are electrically neutral and, therefore, are not attracted to either the anode or the cathode. No conduction occurs along the tube, and the resistance of the gas is said to be "infinite."

As the voltage across the tube increases, the pull exerted upon the electron of the gas atoms by the anode also becomes greater. The electrons, being negatively charged, are pulled toward the anode. The remaining atoms, less several electrons, now are positive ions and are pulled toward the cathode. Because the electrons in the atom are tightly bound to the positive nucleus, the initial pull exerted by the electrodes has no net effect. At some point, however, the pull becomes so great that an electron is torn away from a neutral atom, leaving the atom with one less electron than proton. This process is called "ionization," and the atom is called a "positive ion" due to an excess proton in the nucleus. In general, any atom not electrically neutral is called an "ion"; its charge depends upon whether it has an excess or a deficiency of electrons. The value of the voltage across the tube when ionization occurs is referred to as the "breakdown voltage."

When the voltage across the tube reaches the breakdown voltage, the electrons torn away from the neutral atoms move toward the anode; and the positive ions move toward the cathode (Figure 2). During passage to their respective electrodes, these charge particles undergo collisions with neutral atoms. The collisions can occur with sufficient force to knock electrons loose from other neutral atoms, creating more free electrons and ions in a process called "ionization by collision." This further increases the number of charge carriers and makes even more collisions occur, freeing even more electrons and ions in an avalanche effect. This rapid increase in the number of charge carriers causes a corresponding increase in the

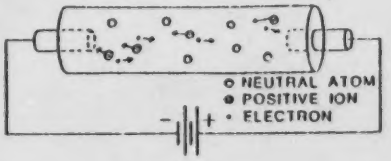


FIG. 2

current through the tube and decreases the voltage across it. These effects combine to decrease the resistance of the tube. When the tube operates in the region through which any increase in current causes a decrease in voltage across the tube, the tube is said to exhibit "negative resistance."

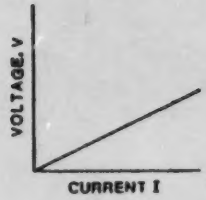


FIG. 3

In order to gain some insight into the concept of negative resistance, the student should examine some devices that exhibit more ordinary behavior: Recall from Module 5E1, "Ohm's Law," that many common materials (metals in particular) obey Ohm's Law. For these materials, called "ohmic" or "linear," the voltage increases in proportion to the current according to the relation presented by Equation 1.

$$V = IR \qquad (1)$$

where

V = voltage across the device.
I = current through the device.
R = resistance.

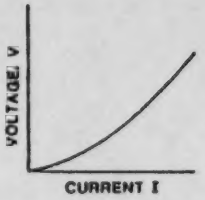


FIG. 4

A graph of voltage plotted against current (called the "V-I characteristic") for an ohmic device is always a straight line as in Figure 3. The resistance is calculated as the slope of the line in the V-I characteristic; and since the slope is constant, so is the resistance. Because this slope is positive for ohmic devices, the resistance also is positive. Devices that exhibit a positive resistance always operate in a stable fashion. Thus, if a voltage is established across the device, the current through it will remain constant.

Many other devices fall into the non-linear class. For these devices (semiconductors and vacuum tubes, for example), the V-I characteristic is not a straight line (Figure 4). The slope of the line, however, is everywhere positive, indicating that semiconductors and vacuum tubes are non-linear devices that exhibit a positive, though changing, resistance and, hence, that operate in a stable manner.

A gas discharge tube (e.g., a gas laser tube) is a non-linear device that exhibits negative resistance (Figure 5). The negative resistance region is recognizable on the V-I characteristic as the portion with a negative slope. In this region, increases in the current through the tube are accompanied by decreasing values of the voltage across the tube. The negative resistance region is very unstable. If the tube is operating in this region, the current will continue to increase, and will be accompanied by decreasing voltage. This process continues until the flat portion

of the V-I characteristic is reached, by which time the current may have become large enough to damage the tube seriously.

The voltage corresponding to the flat portion of the curve is called the "sustaining voltage" and is the smallest value to which the voltage across the tube can fall while the discharge is maintained. The current still can be increased, even after the tube voltage has fallen to the sustaining value. The tube voltage, however, no longer will decrease as current is increased. The region of negative resistance always lies in the range of currents beginning with the breakdown voltage and terminating when the sustaining voltage is reached.

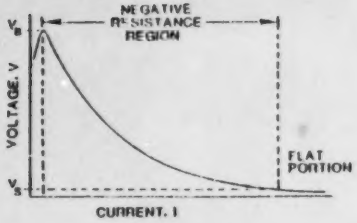


FIG. 5

Figure 6 is a block diagram of a typical gas laser power supply that consists of the following elements: (a) starter, (b) running supply, and (c) current limiter (also called a "ballast resistor").

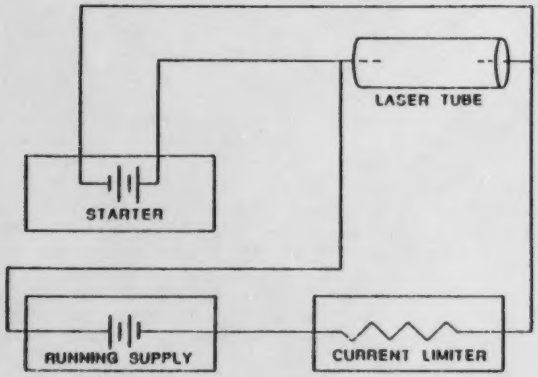


FIG. 6

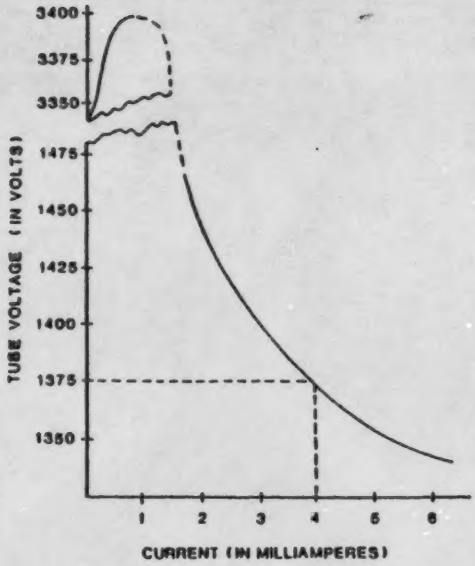


FIG. 7

The purpose of the starter is to generate a d.c. pulse of sufficiently-high voltage to cause ionization of the gas in the laser tube. For this reason, the voltage of the pulse provided by the starter must exceed the breakdown voltage of the gas. Figure 7 is the V-I characteristic of a laster tube containing a mixture of helium and neon gases. For this helium-neon laser, the starter-voltage pulse must be in excess of 3400 V.

Once ionization occurs, however, the high voltage provided by the starter is excessively large for maintaining the discharge. Hence, gas laser power supplies are designed in such a way that the starter element is de-energized when ionization occurs in the tube. The discharge then is maintained by the lower voltage-running supply.

The major function of the running supply is to provide sufficient current and voltage to maintain a continuous discharge through the gas at the desired current level. To accomplish this function, the running supply operates at a lower voltage than the starter and remains on as long as the discharge continues.

It should be noted, however, that, of itself, the running supply cannot maintain a stable discharge through the laser tube because gas lasers are operated in the negative resistance region, where the voltage across the gas depends upon the current through it. Hence, to insure a stable discharge, the current through the tube must be held at some constant value. The method used to achieve constant current employs a current limiter (also called a "ballast resistor") in series with the tube and the running supply.

The function of the ballast resistor is to restrict the current in the circuit to a safe and constant value. The appropriate value of the ballast resistor depends upon three factors:

(a) the desired operating current of the laser.
(b) the voltage output of the running supply.
(c) the V-I characteristic of the laser tube.

The ballast-resistor value is estimated easily from Equation 2.

$$R_B = \frac{V - V_t}{I} \qquad (2)$$

where

R_B = ballast resistance.
V = running supply voltage.
V_t = tube voltage when current is I.
I = current.

EXAMPLE A: BALLAST RESISTANCE FOR A He - Ne LASER

Given: The helium-neon laser described by the V-I characteristic of Figure 7 is to be operated from a 3000-V running supply at a current level of 4mA.

Find: The ballast resistance required.

Solution: $R_B = \frac{V - V_t}{I}$

Use the V-I characteristic (Figure 7) to find V_t when I = 4mA:

V_T = 1375 V

Then:

$$R_B = \frac{3000\ V - 1375\ V}{4 \times 10^{-3}\ A} \quad \text{(Using I in amps)}$$

$$R_B = 406{,}250\ \Omega \simeq 406k\Omega$$

The ballast resistance required to stabilize the current at 4 mA is approximately 406 kΩ.

SUMMARY

The discharge that takes place in a gas laser tube is initialized by a high-voltage pulse that ionizes the gas in the tube. Collisions between neutral atoms and ions increase the conduction through the tube and give rise to the negative resistance region of the laser tube's V-I characteristic. Hence, gas laser power supplies initially must provide a voltage pulse in excess of the breakdown voltage and must limit the current provided by the running supply by means of a ballast resistor. The value of the ballast resistor can be estimated from a knowledge of the running supply voltage and the laser's characteristics.

ELECTRICAL PROPERTIES OF A GAS DISCHARGE TUBE

MATERIALS

Variable d.c. power supply, 0-150 V, 0-1 mA.
Neon bulb.
Microammeter, 0-50 μA.
Vacuum tube voltmeter (VTVM) or electronic digital multimeter (DMM), 0-150 V.
Variable resistor 0-5 MΩ, 0.1 W.

PROCEDURE

1. Connect the circuit shown in Figure 8. Before placing variable resistor in circuit, use ohmmeter on DMM or VTVM to adjust its value to 1MΩ (1×10^6 Ω).

2. Adjust output of power supply to its maximum value of 150 V. Measure and record voltage across power supply V_{max}. Note: The neon bulb should be glowing, indicating that a discharge is taking place.

3. In the Data Table, record the values of current I through the bulb and the voltage V_b across the bulb.

4. Reduce output of power supply until current has decreased approximately 5μA. Record new values of I and V_b in Data Table.

5. Plot this value of V_b versus I on a suitable graph.

6. Repeat Steps 4 and 5 until the current has been reduced to zero and entire V-I characteristic has been plotted. You may need to take data in smaller increments as current is decreased. Draw a smooth curve thorugh points on the V-I characteristic.

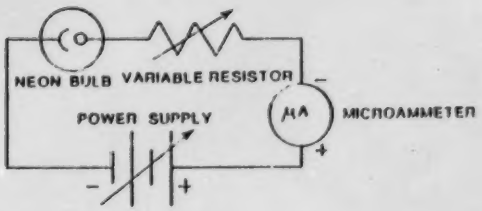


FIG. 8

7. From the V-I characteristic, determine values of breakdown voltage V_B and of the sustaining voltage V_s. Record these values.

8. Choose a point on V-I characteristic near center of negative resistance region. Record V_b and I for this point.

9. Estimate ballast resistance R_B necessary to stabilize current through tube at value chosen in Step 8 when power supply voltage is adjusted to its maximum value. Use Equation 2 with values of $V_t = V_b$, I from Step 8, and $V = V_{max}$ as measured in Step 2.

10. To test your prediction, turn off power supply, and remove variable resistor from circuit. Adjust its resistance to equal R_B (as calculated in Step 9), and replace it in circuit.

11. Turn on power supply and adjust its output to maximum. Measure and record the current through the bulb, and compare it to desired value (from Step 8).

12. Explain how this experiment demonstrates the principles explained in the Discussion section.

DATA TABLE

V_{max} = _____ volts

I(μA)	V_b(V)

V_B = _____ V V_s = _____ V

Point in negative resistance region:

I = _____ μA V_b = _____ V

$$R_B = \frac{V_{max} - V_b}{I} = \_\_\_\_\_ \Omega$$

Measured current = _____ μA

SELF CHECK

1. Define:

   Ion.
   Breakdown voltage.
   V-I characteristic.
   Sustaining voltage.

2. State two ways in which neutral atoms in a gas laser tube can be ionized. Briefly explain each process.

3. Describe the behavior of the voltage across a gas laser tube relative the current through it when the tube is operating in the negative resistance region.

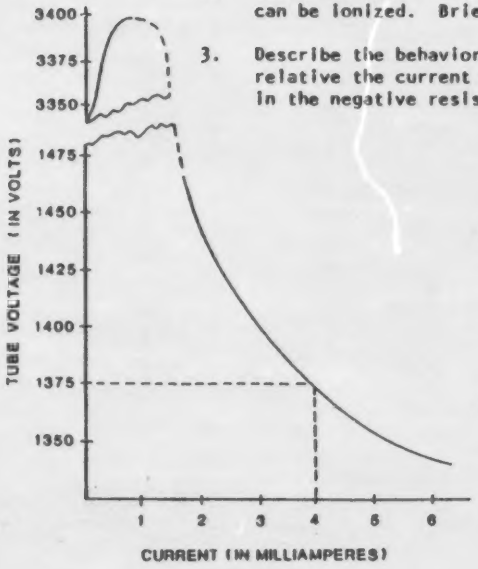


FIG. 9

4. List the three elements of a gas laser power supply, and briefly explain the function of each.

5. A laser described in the adjoining V-I characteristic graph is to be operated from a 2500-V power supply. The desired opearting current is 3.5 mA. Find the ballast resistance necessary to stabilize the current at that value.

6. Determine the breakdown voltage and sustaining voltage for the laser which has the V-I characteristic shown in the adjoining graph. Label the negative resistance region on the graph.

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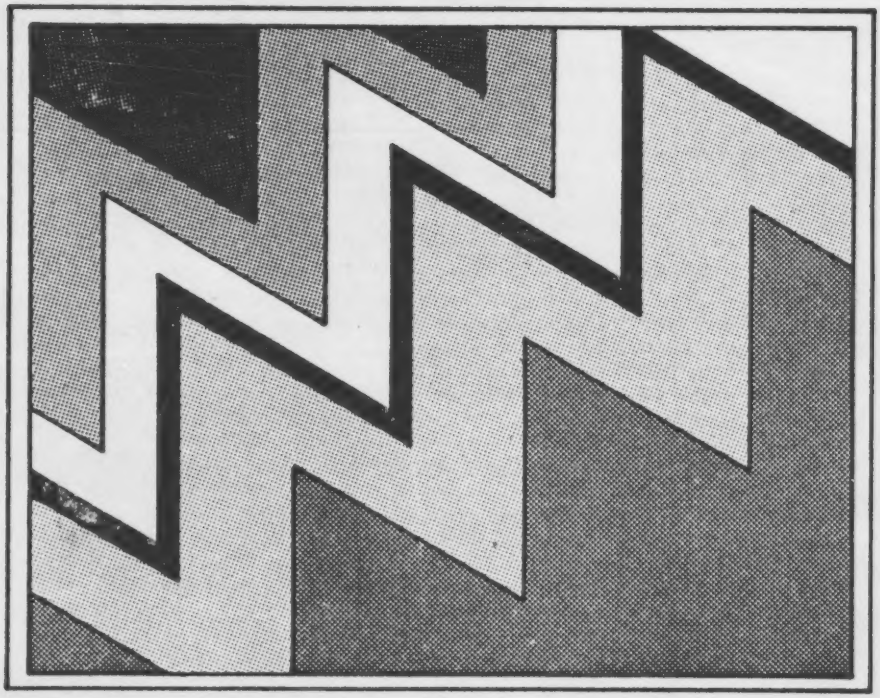
UNIFIED TECHNICAL CONCEPTS

MODULE 5 E 1

OHM'S LAW



ELECTRICAL APPLICATION OF RESISTANCE

Technical Education Research Center – Southwest

TERC – SW

INTRODUCTION

In an attempt to master electricity, scientists first sought to understand its nature and its component parts. After identifying several principal components of electricity, they conducted experiments in an effort to understand better the individual nature of these components and their relationships to each other.

Georg Ohm's contribution began with experiments concerning the relationship of the potential difference, or voltage, between the ends of a metallic conductor and the current flowing through it. What resulted is one of the most important tools for working with electricity and electronics available today. In honor of the discoverer, this tool is called "Ohm's law." This module introduces Ohm's law and its relationship to voltage, current, and resistance. In the laboratory, the student will measure and calculate these three qualities.

PREREQUISITES

Student should have completed Concept Module 5-0, "Resistance," and Application Module 3E1, "Electric Current."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Define voltage, current, and resistance; give their units of measurement.
- Using Ohm's law, calculate resistance, current, or voltage in a circuit, given two of these three quantities.
- Given the appropriate equipment, measure voltage, current, and resistance in electrical circuits having single resistors.

PRINCIPAL COMPONENTS

The three principal components of electricity involved in Ohm's law are voltage, current, and resistance. Voltage can be an electromotive force (emf), or a potential difference. It can be described simply as electrical pressure. Voltage is the electrical component that causes electricity to flow in a circuit. Because it causes the displacement of charge, it plays the role of the forcelike quantity in the electrical system. The unit of measurement for voltage is the volt.

Current is defined as the rate of flow of electrical charge past a point in a conductor when a voltage has been applied. Current is the ratelike quantity in the electrical system. When a potential difference exists between two points (such as between points A and B in Figure 1), the electrons flow from the point of negative potential (-) toward the point of positive potential (+). [Some authors use "conventional" current flow, which is from positive (+) to negative (-), and is not the direction of electron current flow. Rather, "conventional" current flow is opposite to electron flow. It was introduced during the time of Benjamin Franklin, when it was thought that positive charges — rather than negative charges — made up electrical current in ordinary circuits. Today, we know it is the electrons that flow. Either convention can be used as long as it is carefully stated.]

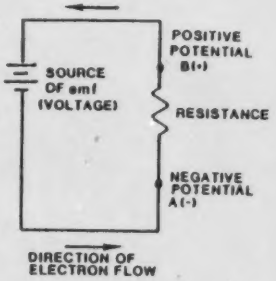


FIG . 1

The unit of measurement for current is the ampere, or amp. An ampere is the current due to one coulomb of charge flowing past a given point in one second (coulomb per second). One coulomb is equal to the charge of 6.28×10^{18} electrons.

The movement of free electrons in a conductor meets with some opposition known as resistance. Resistance can be a useful electrical component. It can be used to limit current flow, it makes the generation of heat possible, and it limits the amount of voltage that can be applied to certain devices.

The resistance of a given conductor is dependent upon four factors:

(1) Type of conductor.
(2) Length of conductor.
(3) Cross-sectional area of conductor.
(4) Temperature.

The unit of measurement of resistance is the ohm. A certain element has a resistance of one ohm when a potential difference of one volt applied to this element maintains a current flow of one ampere through it.

OHM'S LAW

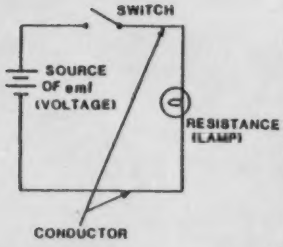


FIG. 2

The simple circuit shown in Figure 2 consists of a source of electromotive force (voltage), a resistance (such as a lamp or a resistor), a switch of some sort, and conductors to serve as circuit wiring.

In 1826, Georg S. Ohm, a German scientist, performed a series of experiments that led to an important law in electricity. Consider a circuit such as that shown in Figure 2. Ohm found that, as long as resistance and temperature remained the same, the current in the circuit was directly proportional to the applied emf. In other words, if emf across the resistance was doubled, current also was doubled. If emf was reduced to one-half the original value, the current was reduced to one-half its original value. The ratio of applied emf to current was constant. This proportionality constant now is called "resistance."

When Ohm went one step further, he found that the value of current changed when he changed the type of bulb (resistance), so long as the conducting wires remained the same. When resistance was increased, the current decreased; and when resistance was decreased, the current increased.

In honor of Georg Ohm's discovery, the unit of resistance is called the "ohm"; and the relationship between these three fundamental components of electricity is called "Ohm's law."

Ohm's law is written as a formula in Equation 1.

$$V = IR \qquad (1)$$

where

V = voltage (electromotive force).
I = current.
R = resistance.

The three equivalent forms of Ohm's law are as follows:

$$V = IR$$

$$I = \frac{V}{R}$$

$$R = \frac{V}{I}$$

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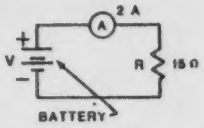
The third form shows resistance as the forcelike quantity (V) divided by the ratelike quantity (I) in the electrical system. Recall that such a ratio yields a measure of the resistance in other energy systems as well.

A simple tool for remembering these three forms of Ohm's law is the Ohm's-law triangle shown in Figure 3. When the unknown quantity is covered, the remaining known quantities will appear in the correct form. For example, if I and R are known, and V is unknown, cover the unknown quantity (V). The known quantities now appear as I x R. Or if V and R are known and I is unknown, cover the unknown quantity (I). The known quantities now appear as V/R. Finally, if V and I are known and R is unknown, cover the unknown quantity (R). The unknown quantities now appear as V/I. These three forms of Ohm's law are used to solve problems in Examples A, B and C.

FIG. 3

EXAMPLE A: VOLTAGE PROBLEM USING OHM'S LAW

Given: The circuit shown in sketch. Circuit resistance is equal to 15 ohms, and current measured by an ammeter is equal to 2 amps.



Find: Voltage necessary for this current to flow.

Solution: $V = IR$

$= (2\ A)(15\ \Omega)$

$= 30\ A\Omega$

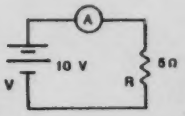
$V = 30$ volts

Voltage required for a 2-A current through the 15-Ω resistor is 30 volts.

EXAMPLE B : CURRENT PROBLEM USING OHM'S LAW

Given: V = 10 V, and R = 5 Ω.

Find: I.



Solution:

$$I = \frac{V}{R}$$

$$= \frac{10\ V}{5\ \Omega}$$

$$= 2\ \frac{V}{\Omega} = 2\ A$$

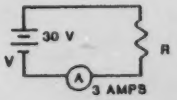
$$I = 2\ A$$

Two amp of current flows through the circuit.

EXAMPLE C : RESISTANCE PROBLEM USING OHM'S LAW

Given: Current = 3 A; electromotive force = 30 V.

Find: R.



Solution:

$$R = \frac{V}{I}$$

$$= \frac{30\ V}{3\ A}$$

$$= 10\ \frac{V}{A}$$

$$R = 10\ \Omega$$

The resistance is equal to 10 ohms.

Basic calculations have been demonstrated using all three versions of the Ohm's law relationship. The solution of any simple circuit problem will be equivalent to one of these examples.

Because of meter inaccuracies, errors in reading the meter, temperature variations, and resistances of resistors varying from rated values, actual readings of current, voltage, and resistance obtained with a VOM or multimeter may not agree always with the mathematical values found by Ohm's law. Even so, results obtained in the following experiments should convince one of the value of the Ohm's-law relationship.

SUMMARY

Ohm's law is one of the most important tools for circuit design and analysis. This law can be stated thusly: "The current in a circuit is directly proportional to the applied voltage and inversely proportional to the resistance of the circuit."

The three equivalent forms of Ohm's law are the following:

(1) $V = IR$

(2) $I = \frac{V}{R}$

(3) $R = \frac{V}{I}$

where

V = voltage (emf).
I = current.
R = resistance.

MEASUREMENT AND CALCULATION OF VOLTAGE

MATERIALS

Several pieces of copper wire (#22).
Variable d.c. power supply (approximately 0 to 20 volts).
Volt-ohm-milliammeter (VOM) similar to Triplett 630 or Simpson 260.
2.2-kΩ, 1/4-watt resistor.

Note: A resistor color-code chart is shown in Figure 4 for those students who are unfamiliar with determining resistor values from color codes.

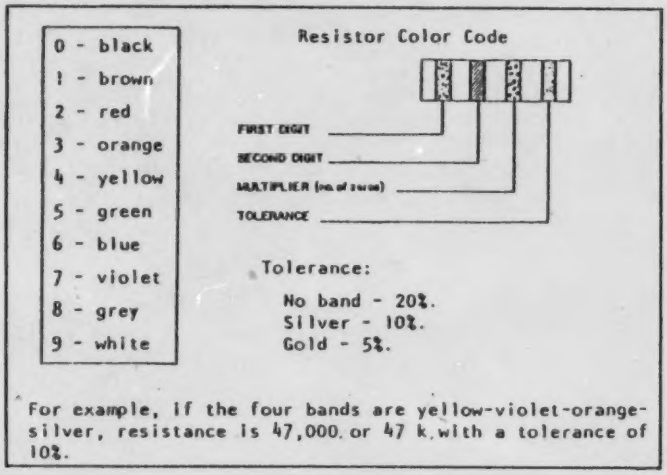


FIG. 4

PROCEDURE

1. Set up circuit as shown in Figure 5. Note: Value of resistor is given in kΩ, kilohms. The prefix "kilo" means 1000. The resistor can, therefore, be identified as 2.2 kilohms, 2.2 x 10 ohms, 2.2 thousand ohms, or 2,200 ohms.

2. Use V = IR to calculate amount of voltage required to cause 8 milliamperes of current to flow in circuit shown in Figure 5. Record in step 4. Note: Current has been given in mA (milliampere). This current level has been

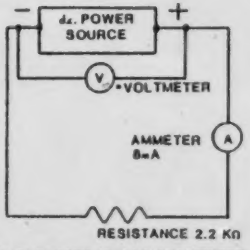


FIG. 5

chosen to minimize danger of electrical shock. Milli is a prefix meaning 1/1000. Therefore, current can be read as 8 mA, 8 milliamperes, 8×10^{-3} amperes, or 0.008 amperes.

3. With variable d.c. power supply set originally on 0 volts, gradually increase voltage until ammeter scale on VOM indicates 8 mA.

4. Remove VOM from ammeter position; connect it as a voltmeter across power supply. Read measured voltage; record.

   V = _____ V (calculated voltage).

   V = _____ V (measured voltage).

5. Calculate percent difference between measured and calculated voltages as follows:

$$\% \text{ difference} = \frac{(\text{calculated value} - \text{measured value})}{\text{calculated value}} (100)$$

6. Do your experimental results tend to confirm Ohm's law? Suggest a few reasons to explain why your theoretical and measured results may not have been in complete agreement.

MEASUREMENT AND CALCULATION OF RESISTANCE

MATERIALS

Several pieces of copper wire (#22).
Variable d.c. power supply (approximately 0 to 20 volts).
Volt-ohm-milliammeter (VOM) similar to Triplett 630 or Simpson 260.
0 to 10-kΩ potentiometer.

PROCEDURE

1. Set up circuit as shown in Figure 6.

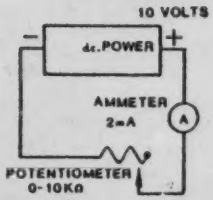


FIG. 6

2. Use Ohm's law to calculate amount of resistance required to cause 2 mA of current of flow when power supply is set for 10 V.

   R = _____ Ω (calculated value).

3. Use VOM as an ohmmeter to verify that potentiometer is set at maximum resistance. As shown in Figure 6, sliding contact should be at topmost position.

4. Set power supply voltage to 10 V, using VOM as a voltmeter across d.c. power source.

5. With VOM connected as an ammeter, reduce resistance of potentiometer until current is increased to 2 mA. (The ammeter itself contributes resistance to the circuit, but it generally is negligible.)

6. Disconnect potentiometer; use ohmmeter to measure its resistance; record below. Be sure to measure across same terminals used in circuit.

   R = _____ Ω (measured value).

7. Calculate percent difference between calculated and measured results.

MEASUREMENT AND CALCULATION OF CURRENT

MATERIALS

Several pieces of copper wire (#22).
Variable d.c. power supply (approximately 0 to 20 volts).
Volt-ohm-milliammeter (VOM) similar to Triplett 630 or Simpson 260.
4.7-kΩ, 1/4-watt resistor.

PROCEDURE

1. Set up circuit shown in Figure 7.

2. Using proper form of Ohm's law, solve for current flowing in circuit shown in Figure 7; record below.

   I = _____ A (calculated value).

3. Set power supply voltage to 15 volts, using VOM as a voltmeter.

4. Connect VOM as an ammeter; measure the current.

   I = _____ mA (measured value).

5. Calculate percent difference between calculated and measured values.

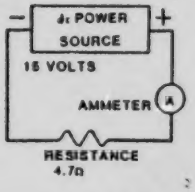


FIG. 7

SELF CHECK

1. Match the word in column A with its definition in B and its units of measurement in C by drawing a connecting line.

A	B	C
Current	Electrical opposition	Volt
Voltage	Rate of flow	Ohm
Resistance	Electrical pressure	Amp

2. What current is drawn by a 8-kΩ electric clock when operated from a 110-V line?

3. A 28-Ω soldering iron requires 5 A for proper operation. What voltage is necessary?

4. What is the effective resistance of a motor if it draws 6 A from a 110-V line?

5. The resistance of an electric percolator is 22 Ω. If it draws 5 A, what is the operating voltage?

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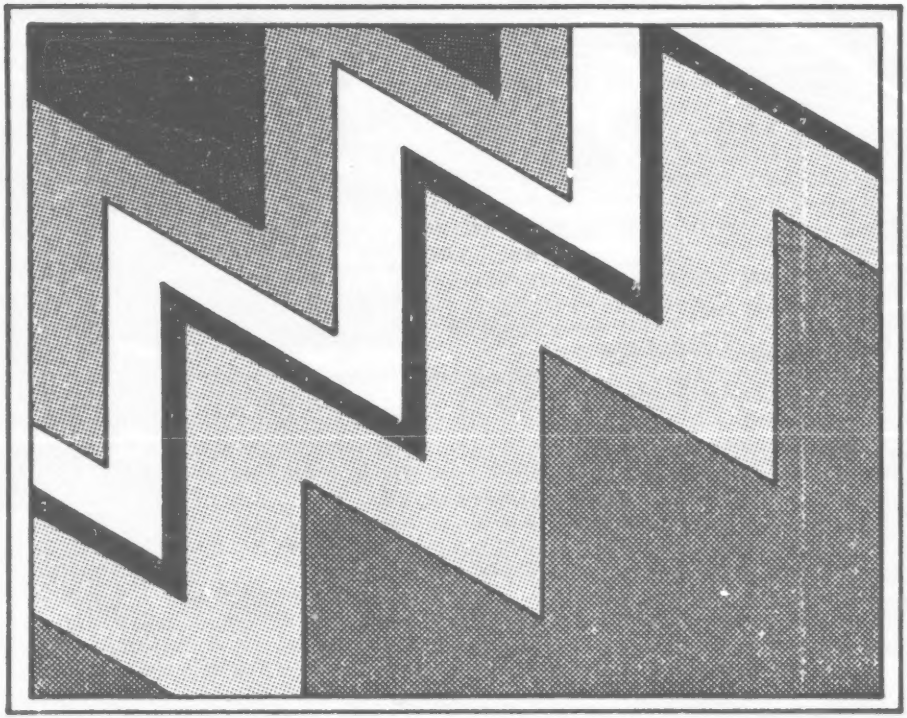
UNIFIED TECHNICAL CONCEPTS

MODULE 5 E 2

SERIES AND PARALLEL RESISTORS



ELECTRICAL APPLICATION OF RESISTANCE

Technical Education Research Center - Southwest

TERC - SW

INTRODUCTION

When there are several electrical devices (appliances, light bulbs, etc.) or components (resistors) to be connected together in a circuit, they are connected in either a series or a parallel manner, or in a combination of both. Resistances connected in series form a single pathway for current flow; resistances connected in parallel form branches, each of which provides a separate path for current flow. Each type of resistance circuit has its own characteristics and uses.

Measurements and calculations often are necessary to determine if a circuit is operating as it should. In the laboratory, the student will use light bulbs as sources of resistance in place of the usual resistors, in order that the affect of series and parallel resistance circuits upon electrical current flow can be observed more directly.

PREREQUISITES

Student should have completed Concept Module 5-0, "Resistance," and Application Module 5E1, "Ohm's Law."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Define the following:

  Series circuit.
  Parallel circuit.
  Overloaded circuit.
  Short circuit.
  Total current in a parallel circuit.
  Total voltage in a series circuit.

- Use Ohm's law to calculate resistance, voltage, and current in simple circuits made up of series and parallel resistances.

- Given the appropriate equipment, measure resistance, voltage, and current in simple circuits.

DISCUSSION

A series circuit is an electrical circuit in which all components are connected in sequence, one after another, to form a single pathway for current flow. Figure 1 shows a string of Christmas lights as an example of a series resistance circuit. Notice that there is only one path through which the current can flow. Current flows from the seat of electromotive force (120-volt line source), through each bulb, and back to the source. There can be only one current, and it must be the same through each lamp. Certain general conclusions can be drawn from this example:

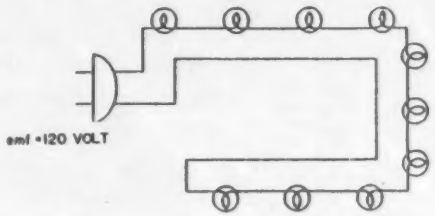


FIG. 1

TEN 12 VOLT BULBS RATED AT 500 MILLIAMPERES EACH

(1) Electrical current in a series circuit is the same through each of the components connected in series, as shown in Equation 1.

$$I_T = I_1 = I_2 = I_3 = \ldots I_N \qquad (1)$$

where

I_T = total current in a series circuit.

I_1, I_2, etc. = current through each component, including as many as there are in circuit (I_N).

(2) Applied voltage in a series circuit is equal to the sum of the voltages across each of the components connected in series. In equation form:

$$V_T = V_1 + V_2 + V_3 + \ldots V_N \qquad (2)$$

where

V_T = total applied voltage (emf) in a series circuit.

V_1, V_2, etc. = voltage across each component, including as many as there are in circuit (V_N).

(3) Ohm's law can be used to show that the total resistance (R_T) of a series circuit is equal to the sum of the resistances of the components (R_1, R_2, etc.). This relationship is given by Equation 3.

$$R_T = R_1 + R_2 + R_3 + \ldots R_N \qquad (3)$$

where

R_T = total resistance of a series circuit.
R_1, R_2, etc. = resistance across component, including as many as there are in circuit (R_N).

Equations 1, 2, and 3 are used to solve a problem in Example A.

EXAMPLE A: SERIES RESISTORS

Given: Each of the ten 12-volt lamps on the string of Christmas lights in Figure 1 is rated at 500 milliamperes (0.5 amperes).

Find:
(a) Resistance of each bulb.
(b) Total current.
(c) Total resistance.
(d) Total voltage.

Solution: (a) Use Ohm's law as follows:

$$R = \frac{V}{I}$$

$$= \frac{12}{0.5 \text{ amps}}$$

$$R = 24\ \Omega$$

(b) $I_T = I_1 = I_2 \ldots$ etc.
I_T = 500 milliamperes (0.5 amperes)

(c) $R_T = R_1 + R_2 \ldots$ etc.
$R_T = 240\ \Omega$

(d) $V_T = V_1 + V_2 \ldots$ etc.
$V_T = 120$ V

The primary advantage of a series circuit is its ability to carry a large number of individual resistances without having to increase the current. Because heat generated in a resistance is related directly to current in the resistance, the advantage of a series circuit for something like Christmas lights is obvious. There is one obvious disadvantage, however, of series circuits: if any one device is burned out or tuned off, the circuit is broken and all current flow ceases.

The disadvantage described above sometimes can be turned into something useful. One switch, placed anywhere in a series circuit,

can control the whole circuit. Some strings of Christmas lights arranged in a series circuit contain one bulb that acts as a flasher switch. When the flasher bulb heats up, a bimetallic strip switch opens, turning all lights off. After the bulb cools, the switch closes, turning the lights back on. A typical flasher bulb is illustrated in Figure 2.

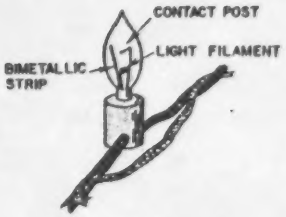


FIG. 2

PARALLEL RESISTORS

In a parallel circuit, electrical components are connected in branches, each of which provides a separate path for current flow. Figure 3 shows a typical automobile electrical system as an example of a parallel resistance circuit.

Notice that there are as many paths for current flow as there are different resistive elements connected in parallel. The current flows from the seat of electromotive force (a 12-volt car battery) simultaneously through each bulb switched into the circuit and then returns to the source. Thus, the total current in the circuit must equal the sum of the individual branch currents. Certain general conclusions can be drawn from this example:

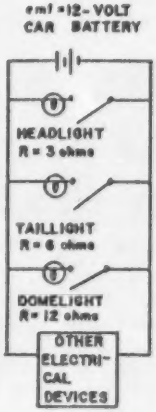


FIG. 3

(1) Total current (I_T) in a parallel circuit is the sum of the currents in each component branch (I_1, I_2, etc.) connected in parallel, as indicated by Equation 4.

$$I_T = I_1 + I_2 + I_3 + \ldots I_N \qquad (4)$$

(2) Voltage across each of the N components (V_1, V_2, etc.) connected in parallel must be equal to the applied voltage. Equation 5 gives this relationship.

$$V_T = V_1 = V_2 = V_3 = \ldots V_N \qquad (5)$$

(3) Electrical current through each of the component branches of a parallel resistance circuit is inversely proportional to the resistance of the branch. Note: the current may be different in each branch. It can be found by applying Ohm's law to each branch:

$$I\ (\text{headlight}) = \frac{V}{R\ (\text{headlight})}$$

and

$$I\ (\text{tail-light}) = \frac{V}{R\ (\text{tail-light})}$$

Equations 4 and 5 are utilized in solving a problem in Example B.

EXAMPLE B: PARALLEL RESISTORS

Given: Voltage across each lamp in Figure 3 is 12 volts (emf), because each lamp is connected directly to the battery through a switch.

Find:
(a) Current through each lamp.
(b) Total current passing through the car battery.
(c) Total effective resistance of the three-lamp circuit.

Solution: (a) Total current in the circuit is equal to the sum of the currents through each of the lamps; thus, using Ohm's law, one can determine the individual currents as follows:

(Headlight current)

$$I_1 = \frac{V}{R_1}$$

$$= \frac{12}{3}$$

$$I_1 = 4 \text{ amps}$$

(Taillight current)

$$I_2 = \frac{V}{R_2}$$

$$= \frac{12}{6}$$

$$I_2 = 2 \text{ amps}$$

(Dome light)

$$I_3 = \frac{V}{R_3}$$

$$= \frac{12}{12}$$

$$I_3 = 1 \text{ amp}$$

(b) Total current passing through car battery.

$$I_T = I_1 + I_2 + I_3$$
$$= 4 + 2 + 1$$
$$I_T = 7 \text{ amps}$$

(c) Again using Ohm's law, total effective resistance of the 3-lamp circuit, so far as the battery is concerned, is the following:

$$R_T = \frac{V}{I_T}$$

$$= \frac{12}{7}$$

$$R_T = 1.7\ \Omega$$

Thus, total resistance of the three parallel branches is less than the individual resistance of any one of the branches. The same result could be found by solving for R_T in Equation 6.

A convenient method of finding the total resistance of resistors in parallel is given in Equation 6.

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \qquad (6)$$

$$\frac{1}{R_T} = \frac{1}{3} + \frac{1}{6} + \frac{1}{12}$$

$$\frac{1}{R_T} = \frac{4 + 2 + 1}{12} = \frac{7}{12}$$

$$R_T = \frac{12}{7} = 1.7\ \Omega$$

There obviously are more than three parallel branches in a typical automobile electrical system. Each additional branch causes the total resistance of the circuit to become lower, thereby causing a greater amount of total current to flow. In fact, a short circuit is basically a parallel circuit branch having negligible resistance.

Lines that carry more than a safe amount of current are said to be "overloaded." To protect against this, fuses or circuit breakers are connected in series with the supply line to "break" the circuit if the current becomes too great.

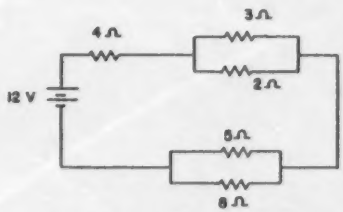
One advantage of a parallel circuit is the possibility of operating electrical devices independently of each other through the use of branch switches. This arrangment is not possible with series wiring. A disadvantage of parallel circuits is the risk of overloading the circuit.

SERIES AND PARALLEL RESISTOR CIRCUITS

Practical electrical circuits often consist of combinations of series and parallel circuits. Because such a great number of combinations of series-parallel circuits is possible, there is no definite procedure that can be followed in solving them. The method depends upon the arrangement. When possible, however, the problem should be solved by replacing each parallel branch with an equivalent series branch. This technique is demonstrated in Example C.

EXAMPLE C: REDUCING A RESISTANCE NETWORK

Given: The circuit shown at the right.



Find: Total current.

Solution: The 2-Ω and 3-Ω resistors in the upper arm of the circuit form a parallel network. By use of Equation 6, they can be reduced to a single equivalent resistance as follows:

$$\frac{1}{R} = \frac{1}{2} + \frac{1}{3} = \frac{3}{6} + \frac{2}{6} = \frac{5}{6}$$

$$= \frac{6}{5}$$

$$R = 1.20\ \Omega$$

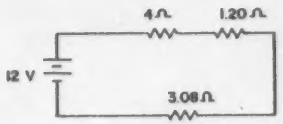
In the same way, the 5-Ω and 8-Ω resistors in the lower arm form a parallel network that can be simplified thusly:

$$\frac{1}{R} = \frac{1}{5} + \frac{1}{8} + \frac{8}{40} + \frac{5}{40} = \frac{13}{40}$$

$$= \frac{40}{13}$$

$$R = 3.08\ \Omega$$

The equivalent circuit now has this appearance:

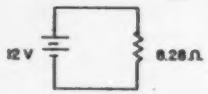


As the circuit is not reduced to one with three resistances

In series, these can be combined to one equivalent resistance by use of Equation 3, as follows:

$$R = 4 + 1.20 + 3.08$$
$$R = 8.28\ \Omega$$

The circuit in its simplest form then looks like this:



Using Ohm's law, the total current in the circuit can be found.

$$I = \frac{V}{R}$$
$$= \frac{12}{8.28\ \Omega}$$
$$I = 1.45 \text{ amps}$$

SUMMARY

The electrical series circuit forms a single path through which current flows; therefore, current has the same value through each component. The parallel circuit contains at least one branch, consisting of two or more paths of current flow. The voltage in each parallel component is the same. Many electrical circuits consist of combinations of series and parallel circuits. The parallel elements often are solved when replaced (in calculations) with series circuits. Total resistance in a series circuit is equal to the sum of the individual resistances; in a parallel circuit, it is calculated either by Ohm's law or by Equation 6.

SERIES AND PARALLEL RESISTANCES

MATERIALS

Five light bulbs (type #233).
Two light bulbs (type #1449).
Seven miniature screw sockets with leads.
Twelve-volt battery or d.c. power supply.
Volt-ohm-milliampere meter (VOM) similar to Triplett 630 or Simpson 260.
Several pieces of No. 22 copper wire.

PROCEDURE

1. Using volt-ohm meter, measure resistance of each #233 and #1449 lamp. Each lamp should have a resistance value within ten percent of a similar lamp. Record measurements in Data Table 1. (Notice that these are "cold" resistances of bulbs.)

2. The #233 lamp is rated at 0.27 amperes with 2.33 volts across its terminals. The #1449 lamp is rated at 0.2 amperes with 14 volts across its terminals. (Notice that these values are determined by "hot" resistance of bulb.) Using this information and Ohm's law, calculate hot resistance for each type of lamp; record results in Data Table 1.

3. Calculate percent difference between average measured cold resistance and calculate hot resistance for each type of lamp. Record results in Data Table 1.

4. Set up series circuit as shown in Figure 4.

5. With VOM meter, measure voltage across each lamp and applied voltage. Record in Data Table 2.

6. Verify that sum of voltages across each lamp is equal to applied voltage. Calculate percent difference if any exists. Record in Data Table 2.

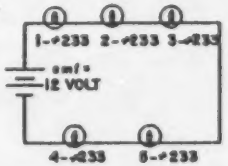


FIG. 4

7. Break circuit between any two #233 bulbs; insert VOM; measure current. Record results in Data Table 3. (Caution: Be sure that scale switch on VOM is initially set on a higher range than expected current.)

8. Using calculated resistance and applied voltage, calculate current through circuit; compare with measured value in Data Table 3.

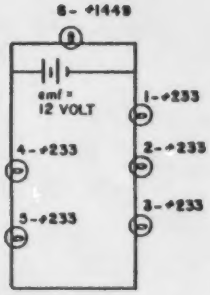


FIG. 5

9. Momentarily short circuit one set of #233 bulb leads; observe effect.

10. Without disturbing existing series circuit, connect a #1449 bulb across power supply as in Figure 5. This is now a series-parallel circuit. Branch containing #1449 bulb is in parallel with branch containing five #233 bulbs in series.

11. Momentarily short circuit one #233 bulb. Note effect of this short on #1449 bulb.

12. Add a second #1449 bulb as shown in Figure 6.

13. Measure current flow through each #1449 bulb and through branch of five #233 bulbs. From these measurements, determine total current delivered by 12-volt source. Record in Data Table 3.

14. Following Example A as a guide, calculate total theoretical current in series-parallel circuit; compare with measured value.

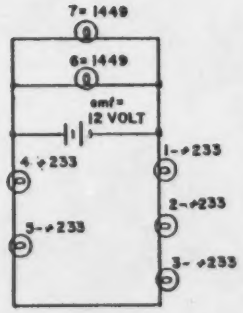


FIG. 6

15. Measure voltage across each #1449 bulb; compare with equation for parallel components in Discussion.

16. What differences would you expect to find in the collected data if commercial resistors were used in place of the light bulbs?

17. Describe and explain effects of the short circuiting in steps 9 and 11.

18. Explain the percent differences found in Data Table 1. (Hint: Recall that resistance depends upon temperature.)

DATA TABLE 1		
"Cold" Resistance' Measured with Ohmmeter	"Hot" Resistance Calculated from Specs.*	Percent Difference**
A. 1 - #233 ____ ohm 2 - #233 ____ ohm 3 - #233 ____ ohm 4 - #233 ____ ohm 5 - #233 ____ ohm Total ____ ohm Average #233 ____ ohm	* #233 - 0.27 A @ 2.33 V * #1449 - 0.2 A @ 14 V $R = \frac{E}{I}$ #233: _____ ohm	** For example: $\% = 2 \frac{\{\text{average cold resistance}\} - \{\text{calculated hot resistance}\}}{\{\text{average cold resistance}\} + \{\text{calculated hot resistance}\}} \times 100$ #233: _____ %
B. 6 - #1449 ____ ohm 7 - #1449 ____ ohm Total ____ ohm Average #1449 ____ ohm	#1449: _____ ohm	#1449: _____ %

DATA TABLE 2	
Measured with Voltmeter	
1 - #233	volts
2 - #233	volts
3 - #233	volts
4 - #233	volts
5 - #233	volts
Sum of voltages	volts
Applied voltage	volts
Percent difference	%

DATA TABLE 3		
Measured with Ammeter	Calculated from Ohm's law	Percent Difference
A.		
1 - 5 - #233 series _____amperes	_____ amperes	_____ %
B.		
6 - #1449 parallel _____amperes	_____ amperes	_____ %
7 - #1449 parallel _____amperes	_____ amperes	_____ %
1 - 5 #233 parallel _____amperes	_____ amperes	_____ %
Total current _____ amperes	_____ amperes	_____ %

SELF CHECK

1. Define or describe the following:

   Series circuit.
   Parallel circuit.
   Overloaded circuit.
   Short circuit.
   Total current of parallel circuit.
   Total voltage of series circuit.

2. If the circuit in Figure 6 were changed from two 1449 bulbs in parallel to six bulbs connected in parallel, what would be the voltage across each of the 1449 bulbs? What would be the total current supplied by the battery?

3. If the series circuit of five 233 bulbs were increased to eight 233 bulbs in series, what would be the voltage across each lamp? Does the brightness of the bulbs change; if so why?

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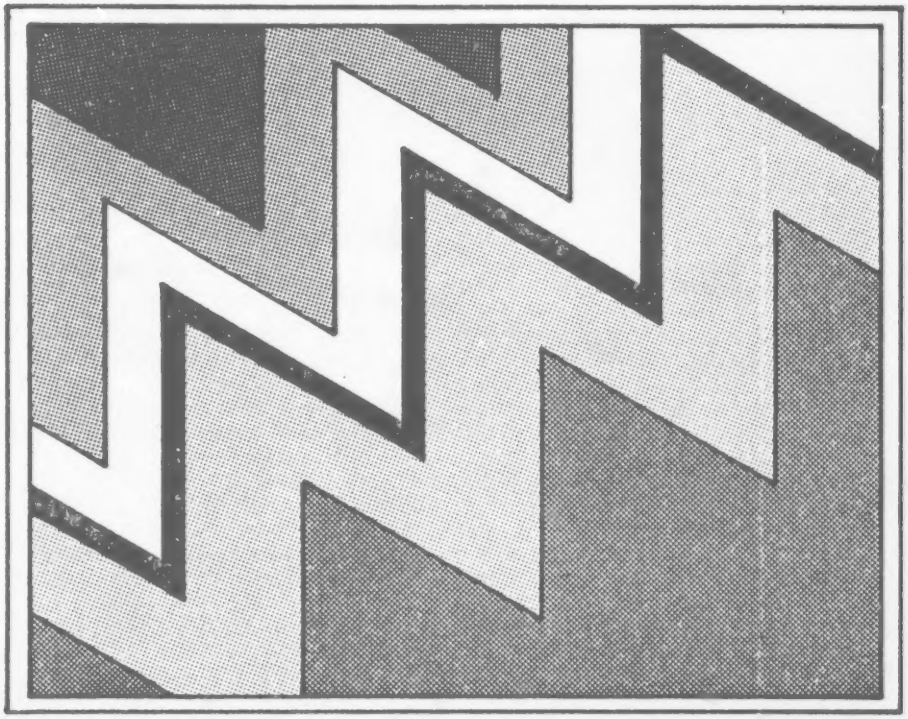
UNIFIED TECHNICAL CONCEPTS

MODULE 5 E 3

INTERNAL RESISTANCE OF A BATTERY



ELECTRICAL APPLICATION OF RESISTANCE

Technical Education Research Center - Southwest

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180

INTRODUCTION

Electrical applications of the resistance concept are familiar, but resistance of the power source in a circuit is often neglected, as it is usually a small value compared with the other elements in the system. In this module, applications will be considered in which the total circuit resistance is low enough to cause internal resistance of the battery to become significant. A method for making electrical measurements that may be used to compute the battery's internal resistance will be outlined.

PREREQUISITES

Student should have completed Concept Module 5-0, "Resistance," and Application Module 5E1, "Ohm's Law."

OBJECTIVES

To complete this module, the student should be able to:

- Define electrical current and electromotive force.
- Write the formula for Ohm's law and explain each symbol.
- Draw a schematic diagram that includes a battery as a resistive element of an electrical circuit.
- Provided with a battery and necessary circuit components, determine internal resistance of the battery.

DISCUSSION

Concept Module 5-0, "Resistance," points out that resistance is the phenomenon that causes a ratelike quantity to decrease to zero in the absence of a forcelike quantity. In the electrical application, resistance causes current (rate of movement of charge through the circuit) to decrease to zero when the potential difference is removed from two points in the circuit.

Electrical resistance is defined by Ohm's law:

$$R = \frac{V}{I} \qquad (1)$$

where

R = resistance of a circuit element.
V = potential difference across resistive element.
I = current sustained by potential difference in the resistive element.

Values of resistance are given in ohms, potential difference in volts and current in amperes.

A battery in an electrical circuit causes current to flow because of energy stored in it. Potential difference across the electrodes of a battery is called electromotive force (emf). Measurements of emf are represented by the symbol (E) and are expressed in volts.

As a component of the circuit, the battery is also a resistor. The battery electrolyte (active chemical materials), plate separators and conductive elements all tend to restrict somewhat the flow of current. In this module, the symbol (r) will represent internal resistance of the battery. Table 1 lists units of measurement required in this module.

TABLE 1. SI UNITS FOR ELECTRICAL MEASUREMENTS

Measurement	Symbol	Unit
Potential difference	V	Volts
Electromotive force	E	Volts
Current	I	Amperes
Resistance	R	Ohms
Battery internal resistance	r	Ohms

Value of a battery's internal resistance may be found by electrical measurement. The circuit required for this procedure is shown as a schematic diagram in Figure 1.

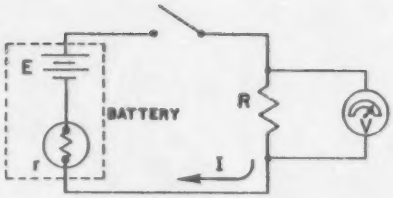

Fig. 1

Internal resistance of the battery is indicated as a resistor in series with the source of emf. When the circuit is closed, potential difference across the external resistance (R) is, by Ohm's law:

$$V = IR. \qquad (2)$$

Actually, since the emf is causing current to flow through all of the elements in series, a similar statement may be written to include the battery internal resistance:

$$E = IR + Ir. \qquad (3)$$

Subtracting Equation 2 from Equation 3 and solving for r gives the following expression for internal resistance:

$$r = \frac{(E - V)}{I} \qquad (4)$$

where

- E is measured when the circuit is open; if current is flowing, the measurement of potential difference across the battery is influenced by its internal resistance.
- V is measured directly across end of the external resistance. Note that this is also the potential difference across the battery with current flow.
- R is known.
- I is known by the Ohm's law relationship.

A working equation for the experimental determination of the internal resistance of battery is then:

$$r = (E - V) \times \left(\frac{R}{V}\right). \qquad (5)$$

Internal resistance of a battery depends upon rate of discharge of the battery because condition of the battery electrolyte is affected by discharge rate. Other factors that influence internal resistance are temperature, state of charge and age of the battery. Internal resistance data, then, may vary considerably with overall condition of the battery.

MATERIALS

6-volt lantern battery with screw cap terminals.
Knife switch with screw terminals.
Four selected resistors in the range of 1 to 10 ohms. (Only resistors that have been calibrated by the manufacturer or by accurate measurement to within 1% should be used.)
Resistor power ratings should exceed $E^2/R = 36/R$ for this experiment.
d.c. voltmeter with a full-scale range of ten volts.
Three pieces of 10- to 12-gage cable with terminal lugs for series connection of the electrical circuit.

PROCEDURES

1. Measure emf of the battery; record value in column E of data table. Remember that this must be done with battery separate from any circuit and with a voltmeter that draws no current.
2. Begin with largest value resistor in set of four. Connect battery, knife switch and resistor in series. Record resistance value in column R of data table.
3. Connect voltmeter to ends of resistor.
4. Close knife switch. Watch meter needle sweep rapidly to a fairly steady value. Try to make a reading within a couple of seconds after that level is reached. Open switch; record voltage in data table, column V.
5. Refer to Equation 5; compute value of battery internal resistance. Record answer in data table, column r.
6. Repeat procedures 1 through 5, using other resistance values; complete data table.

DATA TABLE

R Resistor Value	E Volts	V Volts	r Ω

SELF CHECK

1. Draw a schematic diagram that shows a battery as a resistance element of an electrical circuit.
2. Compute internal resistance of a battery, given the following information:
   An automobile battery is found to have an open circuit emf of 12.2 volts.
   A starter motor has an "IR drop" of 5.0 volts when operating at 500 amps.
   When connected to the given battery, voltage across the starter motor is 6.1 volts.
3. Write a brief discussion of the experimental procedure; explain any variations observed in results.

REFERENCES

Union Carbide Corporation. Eveready Battery Applications and Engineering Data. New York: Union Carbide Corp., 1968.

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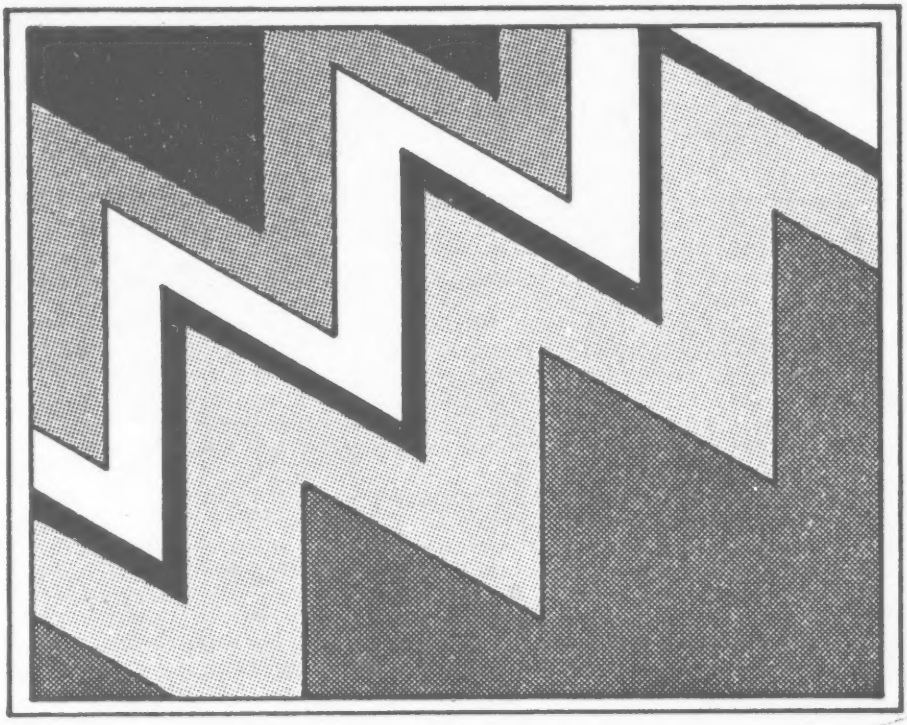
UNIFIED TECHNICAL CONCEPTS

MODULE 5 E 4

CONDUCTORS, SEMICONDUCTORS, AND INSULATORS



ELECTRICAL APPLICATION OF RESISTANCE

Technical Education Research Center – Southwest

TERC – SW

INTRODUCTION

One of the more important considerations when choosing materials to be used in electrical and electronic circuits is the material's ability to conduct an electrical current. Based upon their resistance to current flow, all materials fall into one of three classes:

Conductors.
Insulators.
Semiconductors.

Familiarity with each of these classes is important in the effective use of electricity.

In this module, the student will examine the electrical properties of conductors, insulators and semiconductors. In the laboratory, the student will measure the resistance of several material samples, and will compare their characteristics.

PREREQUISITES

Student should have completed Concept Module 5-0, "Resistance," and Application Module 5E1, "Ohm's Law."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Define:

  Ionic bonding.
  Covalent bonding.
  Metallic bonding.
  Insulator.
  Conductor.
  Semiconductor.

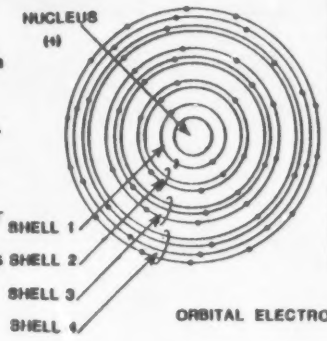
- Explain why the electrical resistance of metals increases as temperature increases.

- Explain why the resistance of semiconductors decreases as temperature increases.
- Given resistances of conductors, semiconductors and insulators, explain the difference in values for each group.
- Explain why practical electrical insulators use covalent-bonded material instead of ionic-bonded material.
- Given the appropriate equipment, measure the resistance of several materials and compare their characteristics.

DISCUSSION

Whether a material is an insulator, a conductor or a semiconductor is determined by its atomic structure.

An atom is composed of a positively-charged nucleus, or core, surrounded by negatively-charged electrons. The electrons orbit the nucleus in a definite pattern of shells and subshells. Figure 1 shows the first four electron shells of an atom. It also shows that shell 2 has 2 subshells, shell 3 has 3 subshells, and shell 4 has 4 subshells.



SHELL	SUBSHELL	ELECTRONS	TOTAL
1	S	2	2
2	S P	2 6	8
3	S P D	2 6 10	18
4	S P D F	2 6 10 14	32

FIG. 1

The energy of an electron is related to its average distance from the nucleus, with the closest electron being the least energetic. In the formation of an atom, electrons naturally fill the lower energy levels first. Helium, for example, has two electrons, both of which lie in the first shell. Copper has 29 electrons. Its first three shells are filled, with one electron left over. This remaining electron occupies the s subshell of the fourth shell (2 + 8 + 18 + 1 = 29).

The most stable configuration for any atom is to have its subshells filled. The atoms' attempt to have filled subshells causes bonding between atoms.

IONIC BONDING

Figure 2 shows an atom of sodium (Na) with 11 electrons and an atom of chlorine (Cl) with 17. Ten of the sodium electrons fill the first three subshells of sodium, leaving one extra electron. Chlorine, on the other hand, needs one more electron to fill its fifth subshell. The sodium atom gives up its electron to the chlorine atom as shown in Figure 2.

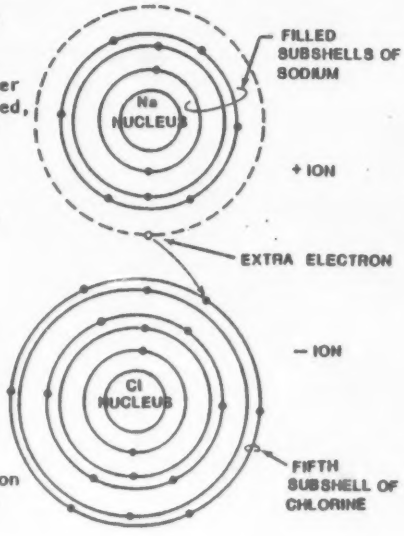


FIG. 2

Because the atoms are neutral (have no net charge) to begin with, losing one electron gives the sodium atom a charge of +1, and gaining one electron gives the chlorine atom a charge of -1.

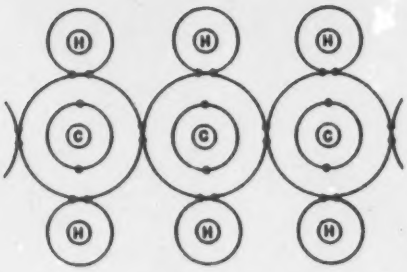


FIG. 3

The attraction of unlike charges holds the two charged atoms, or ions, together. This attraction is called "ionic bonding."

COVALENT BONDING

A second way in which atoms may fill their outer subshells is shown in Figure 3, in which the structure of Polyethylene molecules is illustrated. There, each carbon atom (C) needs four additional electrons to fill its outer subshell, and each hydrogen atom (H) needs one additional electron. All these subshells are filled by sharing electrons. Each carbon atom shares one electron from two hydrogen atoms and two adjacent carbon atoms. This sharing of electrons is called "covalent bonding."

METALLIC BONDING

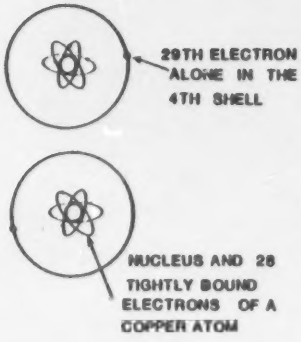


FIG. 4

A third method of bonding occurs in metals. Figure 4 shows two copper atoms. The single electron in the 4s subshell of each atom is very loosely bound to the atom. In a solid piece of copper, the attraction between this electron and the nucleus is too weak to hold the electron in its orbit. The electron does not really "belong" to any one copper nucleus; therefore, it is free to move throughout the piece of copper. The copper actually consists of an array of positive copper ions suspended in a "cloud" of free electrons. The repulsive forces between the positive copper ions causes them to have fixed positions within the electron cloud. The attractive forces between the positive ions and the negative electrons holds the copper together and is called "metallic bonding."

INSULATORS, CONDUCTORS AND SEMICONDUCTORS

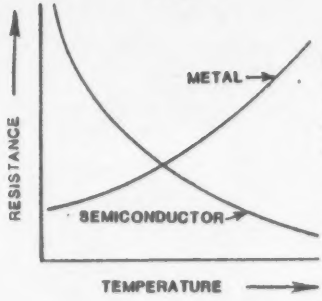


FIG. 5

Insulators are materials whose outer electrons are bound tightly to the atoms and cannot serve as charge carriers. The bond may be either ionic or covalent. Materials commonly employed as electrical insulators are usually covalent, because this type of bonding is not broken down as easily as ionic bonding.

Conductors are materials whose outer electrons are free to move throughout the material. How well a material conducts electricity depends upon how many free electrons it has per unit volume and upon the rate at which the electrons collide with the atoms in the material. As a conductor is heated, random motion of free electrons speeds

up, and the atoms themselves vibrate about their fixed positions. This increases the rate of electron collisions, thus increasing the resistance. Figure 5 shows the effect of temperature on the resistance of both metals and semiconductors. Although resistance of metals increases with temperature, resistance of a semiconductor decreases. This behavior is explained in the following paragraphs.

Semiconductors are materials that are ordinarily rather good insulators but can be made to conduct by supplying a small amount of extra energy, as, for example, by raising the temperature.

Some of the best-known semiconductors are materials in which the outer subshell of atoms has four electrons and needs another four electrons to fill the subshell completely. These semiconductors include carbon (6 electrons), silicon (14 electrons) and germanium (32 electrons). Such materials form a crystalline structure through covalent bonding, as shown in Figure 6.

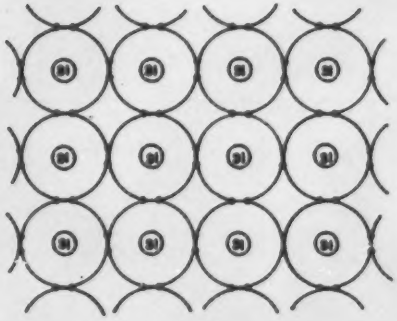


FIG. 6

Because all of the outer electrons are involved in covalent bonds, there are no free electrons. These loosely-bound, or so-called "valence," electrons, however, are barely attached to the atoms. Some of them can be moved by adding only a small amount of extra energy. For this reason, the resistance of semiconductors is high at low temperature, but decreases greatly as the temperature rises.

Figure 7 gives relative resistivities of several insulators, semiconductors and conductors. The resistivity of a materal depends

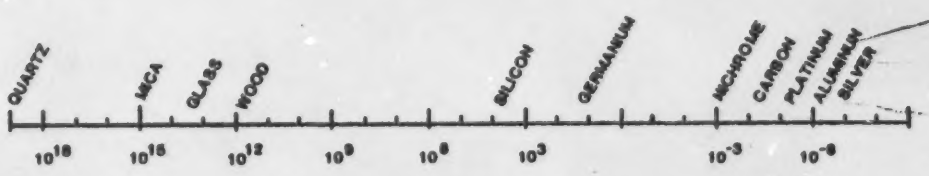


FIG. 7

upon the material, and is measured in ohm-meters. Resistance of a material is always proportional to the resistivity. For a material of given length and cross section, the higher the resistivity, the higher the resistance. As indicated in Figure 7, quartz is a good insulator (high resistivity) and, thus, a poor conductor. On the other hand, silver is a good conductor (low resistivity) and, thus, a poor insulator. Silicon and germanium, somewhat "in-between" on the resistivity scale, are classified as semiconductors.

The resistance of a material can be found by use of Equation 1.

$$R = \rho\frac{\ell}{A} \qquad (1)$$

where

R = resistance.
ρ = resistivity of material.
ℓ = length of material.
A = cross-sectional area of material.

SUMMARY

Whether a material is a conductor, an insulator, or a semiconductor depends upon its ability to conduct an electrical current. The conductor possesses low resistance to current flow; the insulator, high resistance; and the semiconductor, high resistance when at low temperature and low resistance at high temperature. Ionic, covalent and metallic bonding within atoms determines conductivity.

RESISTANCE MEASUREMENT AND CHARACTERISTICS OF MATERIALS

MATERIALS

Several meters of number 36 or 38 enameled copper wire.
Several meters of number 28 or 32 nichrome wire.
Carbon rod (refill lead for a mechanical pencil).
Silicon or germanium transistor.
Glass rod 2 mm in diameter, 5 cm long.
Matches.
Volt-ohm-milliammeter (VOM) or multimeter.

PROCEDURE

1. Make a coil of each piece of wire, being careful to leave ends exposed for electrical connections, and not allowing any part of coil to overlap.

2. Connect volt-ohm-milliammeter across each sample; measure resistance; record in Data Table.

3. Heat each sample with a match; observe change in resistance. Record resistance when heated.

4. Complete Data Table, indicating whether each material tested is an insulator, semiconductor or conductor.

5. In an electrical circuit operated at high temperature, which material in the Data Table would serve as the best conductor?

DATA TABLE			
Material	Resistance at Room Temperature (Ω)	Resistance When Heated (Ω)	Type of Material (Insulator, Semiconductor, Conductor)
Copper wire			
Nicrome wire			
Carbon rod (pencil lead)			
Silicon or germanium			
Glass			

SELF CHECK

1. Define:

   Ionic bonding.
   Covalent bonding.
   Metallic bonding.
   Insulator.
   Conductor.
   Semiconductor.

2. Explain why resistance of a copper wire increases when it is heated.

3. Explain why resistance of a carbon rod decreases when it is heated.

4. Explain why copper is a better conductor than carbon.

5. Explain why glass is a poor conductor.

6. Why are materials with ionic bonding seldom employed as electrical insulators in practical circuits?

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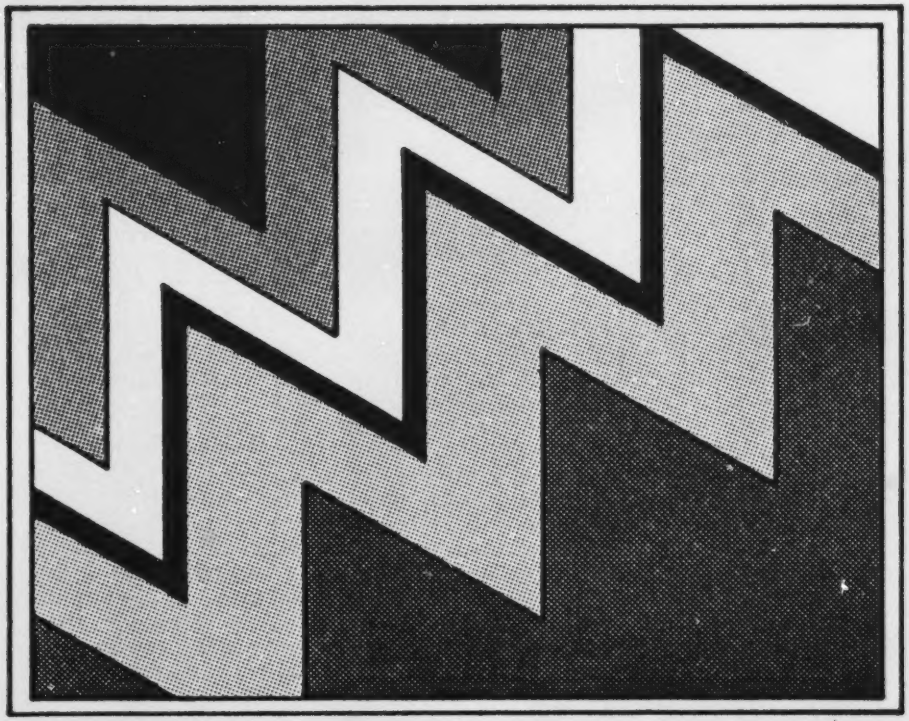
UNIFIED TECHNICAL CONCEPTS

MODULE 5 E 5

RESISTANCE OF WIRES



ELECTRICAL APPLICATION OF RESISTANCE

Technical Education Research Center – Southwest

TERC – SW

INTRODUCTION

The resistance of an electrical conductor, such as a wire, depends upon the material from which it is made, its shape and its temperature.

In this module, the student will investigate the effect of each of these quantities. In the laboratory, the student will determine the resistance of wires at different temperatures.

PREREQUISITES

Student should have completed Concept Module 5-0, "Resistance," and Application Module 5E1, "Ohm's Law."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Calculate resistance of a conductor at room temperature, given its dimensions and composition.
- Calculate resistance of a conductor at any temperature, given its dimensions and composition.
- Given the appropriate equipment, determine the resistance of wires at varying temperatures.

Resistance is an inherent property of a conductor. The resistance of a conductor of uniform cross-sectional area is dependent upon four factors:

- Composition (the material from which it is made).
- Length.
- Cross-sectional area.
- Temperature.

The German physicist Georg Ohm stated that resistance of a conductor at a given temperature is directly proportional to its length, inversely proportional to its cross-sectional area and dependent upon the material from which it is made. The effect of the material itself is represented by a quantity called "resistivity," which is explained in the following paragraph. Equation 1 shows this relationship in a formula.

$$R = \rho \frac{\ell}{A} \qquad (1)$$

where

R = resistance.
ρ = resistivity.
ℓ = length.
A = cross-sectional area.

RESISTIVITY

Current in a conductor is the movement of free electrons. Resistance — the opposition to this movement — is present in varying degrees in different materials. Resistance is high when relatively few free electrons are available for conduction and when they move with difficulty through the material. This property, represented by the Greek letter ρ, is called resistivity of the material. When Equation 1 is solved for resistivity, Equation 2 is formed.

$$\rho = R \frac{A}{\ell} \qquad (2)$$

A simple meaning for the quantity ρ can be found. Imagine a sample of material with unit cross-sectional area A and unit length ℓ. When these values are substituted in the equation, ρ is simply R, the resistance of the sample. Hence, the resistivity of a material is the resistance to current offered by a unit cube of the material. A dimensional analysis of Equation 1 shows that ρ must have dimensions of resistance times length. ρ usually is expressed in units of ohm-meters or ohm-centimeters. The resistivities of several common conductors are given in Table 1, together with their temperature coefficients of resistance, to be explained later in

this module. Because these quantities depend on temperature, they are given at 20°C, which is roughly "room temperature."

FIG. 1

TABLE 1: RESISTIVITY AND TEMPERATURE COEFFICIENTS OF VARIOUS MATERIALS AT 20°C (293°K)

Material	Resistivity (ρ) (Ω - m)	Temperature Coefficient of Resistance (α) (per °C)
Silver	1.47×10^{-8}	0.00411
Copper	1.72×10^{-8}	0.00426
Aluminum	2.63×10^{-8}	0.00420
Tungsten	5.51×10^{-8}	0.0049
Constantan	4.41×10^{-7}	less than 0.00001
Nichrome	1.50×10^{-6}	0.00044

LENGTH

The longer the path the electrons are forced to travel, the more resistance they will encounter. Figure 1 shows that when the length of a wire is doubled, the number of atoms that impede electron progress doubles, thereby doubling resistance. Atoms are shown as ⊕ , free electrons shown as ⊖→.

A nichrome wire 10 meters long offers 10 times greater resistance than a nichrome wire 1 meter long.

CROSS-SECTIONAL AREA

The greater the cross-sectional area of a conductor, the lower the resistance. Figure 2 shows that when cross-sectional area A is doubled, twice as many electrons are allowed to move through it, thus doubling the current I. The effective resistance for the same length ℓ then is only one-half as great.

Example A illustrates the use of Equation 1 in solving a problem.

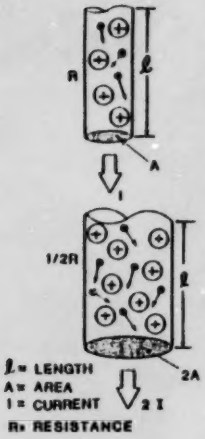


FIG. 2

EXAMPLE A: RESISTANCE OF A COPPER WIRE

Given: A copper wire at 20°C with a diameter of 0.1 millimeters and a length of 50 meters.

Find: Resistance. (Refer to Table I for resistivity.)

Solution: $R = \frac{\rho \ell}{A} \quad \frac{\rho \ell}{\pi r^2}$ (Recall: $A = \pi r^2$.)

$$= \frac{(1.72 \times 10^{-8}\ \Omega \cdot m)(50\ m)}{(3.14)(5 \times 10^{-5}\ m)^2} = \frac{86 \times 10^{-8}\ \Omega \cdot m^2}{(3.14)(25 \times 10^{-10}\ m^2)}$$

$$= \frac{860 \times 10^{-7}\ \Omega \cdot m^2}{7.85 \times 10^{-9}\ m^2}$$

$$= 1.09 \times 10^{2}\ \Omega$$

$$R = 109\ \Omega$$

Resistance of the wire at 20°C is 109 ohms.

TEMPERATURE

Temperature is the fourth condition which affects the resistance of a conductor. The greater the temperature of a conductor, the greater is the vibration of its atoms; and the greater is its hindrance to electron flow. Dependence of resistance upon temperature is not the same for all materials. For the most common conductors, resistivity increases as temperature increases. Change in resistance per degree of temperature change for a one-ohm sample of a material is called the "temperature coefficient of resistance" (α) of the material. Values for a few materials are given in Table I. Units are simply reciprocal degrees of temperature.

$$R_T = R_o\ [1 + \alpha\ (T - T_o)] \qquad (3)$$

where

R_T = resistance at any temperature T.
R_o = resistance at temperature T_o, often taken to be 20°C or 0°C.
α = temperature coefficient of resistivity for particular material.
$T - T_o$ = temperature change.

In Equation 3, the change in resistance resulting from the temperature change $T - T_o$ is given by $\alpha\ (T - T_o)$.

Examples B, C, and D consist of problems solved by use of Equation 3.

EXAMPLE B: EFFECT OF TEMPERATURE ON RESISTANCE

Given: A silver wire with a resistance of 100 ohms at 20°C.

Find: Its resistance at 300°C.

Solution:

$$R_T = R_o [1 + \alpha (T - T_o)]$$

$$R_{300} = 100\ \Omega\ [1 + (0.00411)(300 - 20)]$$

$$= 100\ \Omega\ [1 + (0.00411)(280)]$$

$$= 100\ \Omega\ (1 + 1.15)$$

$$= 100\ \Omega\ (2.15)$$

$$R_{300} = 215\ \Omega$$

Resistance more than doubles!

The most common conductors for which these equations give useful results are wires. The accepted standard for specifying the size or wire is the American Wire Gage. Table 2 is provided in order that problems may be worked using this nomenclature.

TABLE 2: AMERICAN WIRE GAGE VALUES AT 20°C

Gage No.	Diameter (mm)	Cross-sectional Area (mm^2)
8	3.264	8.367
14	1.628	2.082
20	0.8118	0.5176
24	0.5106	0.2048
26	0.4049	0.1288
36	0.1270	0.01267
38	0.1007	0.007964
40	0.07987	0.005010

Examples C, D and E show how to use Equations 1 and 3 to solve problems.

EXAMPLE C: RESISTANCE OF A #36 TUNGSTEN WIRE

Given: A 4-meter length of number 26 tungsten wire is to be used at a temperature of 600°C.

Find: Its resistance.

Solution:

$$R_T = R_o [1 + \alpha (T - T_o)] \qquad \left(R_{20} = \frac{\rho \ell}{A}\right)$$

$$= \rho \frac{\ell}{A} [1 + \alpha (T - 20)]$$

$$= \frac{(5.51 \times 10^{-8}\ \Omega \cdot m)(4\ m)}{1.267 \times 10^{-6}\ m^2} [1 + (4.9 \times 10^{-3}\ °C^{-1})(600 - 20°C)]$$

$$= (17.4\ \Omega)(1 + 2.84)$$

$$= 17.4\ \Omega\ (3.84)$$

$$R_T = 66.8\ \Omega$$

EXAMPLE D: RESISTANCE OF A #24 COPPER WIRE

Given: No. 24 copper wire.

Find: What length will have a resistance of 1 ohm at 5°C.

Solution:

$$R_T = \rho \frac{\ell}{A} [1 + \alpha (T - 20)]$$

$$\ell = \frac{R_T A}{\rho [1 + \alpha (T - 20)]}$$

$$= \frac{(1\ \Omega)(2.047 \times 10^{-7}\ m^2)}{(1.72 \times 10^{-8}\ \Omega \cdot m)[1 + (4.26 \times 10^{-3}\ °C^{-1})(5 - 20°C)]}$$

$$= \frac{2.047 \times 10^{-7}\ \Omega \times m^2}{(1.72 \times 10^{-8}\ \Omega \cdot m)[(1 + 4.26 \times 10^{-3}\ °C^{-1})(-15°C)]}$$

$$= \frac{2.047 \times 10^{-7}\ \Omega \cdot m^2}{(1.72 \times 10^{-8}\ \Omega \cdot m)(0.937)}$$

$$\ell = 12.7\ m$$

The required length of copper wire is 1.27 m.

Note: The negative indicates a decrease in temperature from 20°C.

EXAMPLE E: RESISTANCE OF NICHROME WIRE

Given: A piece of nichrome wire with a resistance of 25 ohms at 20°C.

Find: The temperature at which it will have a resistance of 28 ohms.

Solution: $R_T = R_o [1 + \alpha (T - T_p)]$

Solving for T,

$$T = 20°C + \frac{(R_T/R_{20} - 1)}{\alpha}$$

$$= 20°C + \frac{(28\ \Omega/25\ \Omega - 1)}{4.4 \times 10^{-4}\ °C^{-1}} = 20°C + \frac{0.12}{4.4 \times 10^{-4}}\ °C$$

$$= 20°C + 273°C$$

$$T = 293\ °C$$

Thus, nichrome wire increases its resistance from 25 ohms to 28 ohms when temperature increases 273°C above room temperature of 20°C.

SUMMARY

The degree of resistance of a wire depends upon its composition, length, cross-sectional area, and temperature. A wire possessing good conductance has low resistance. A wire having strong resistance will rise in temperature and in resistance when current is increased through it.

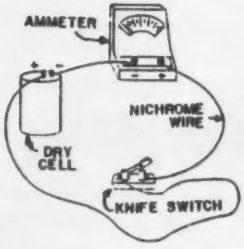
RESISTANCE OF WIRES AT DIFFERENT TEMPERATURES

MATERIALS

Dry cell (1.5 volt).
Switch (knife or key).
Ammeter.
Nichrome wire (#36 or #38).
Copper wire (#38 or #40).

PROCEDURE

1. Use a piece of nichrome wire 50 centimeters long, to connect a circuit as shown in Figure 3.
2. Close circuit; record immediate "cold" current in Data Table.
3. Allow current to flow for 30 seconds to heat nichrome wire. Record "hot" current that seems to remain constant.
4. Open circuit; allow nichrome wire to cool. Remove wire from circuit; fold it in two; twist it so it forms a piece of wire 25-cm long having twice the cross-sectional area.
5. Insert this resistance into circuit; record "cold" current.
6. Allow wire to heat as before; record "hot" current that remains constant.
7. Remove this wire; replace it with a 25-cm length of nichrome wire of same gage. Record "cold" and "hot" currents as before.
8. Repeat steps 1 through 7, using 10-meter and 5-meter lengths of copper wire.
9. Using Ohm's law, R = V/I, calculate "cold" and "hot" resistance for each trial; record.
10. Assume temperature at "cold" resistance to be 20°C. Use tables and equations in this module to calculate temperature of wire at "hot" resistance for each trial; record.
11. Explain how the results of this experiment show the applications of Equations 1 and 2.



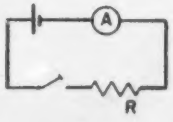


FIG 3

DATA TABLE								
				Current		Resistance		
Trial	Material	Length	Area	Cold	Hot	Cold	Hot	Temperature
1	Nichrome	50 cm	A					
2		25 cm	2A					
3		25 cm	A					
4	Copper	10 m	A					
5		5 m	2A					
6		5 m	A					

SELF CHECK

1. Calculate the resistance of each of the following:

   20 m of number 8 copper wire at 20°C.
   100 m of number 14 silver wire at 135°C.
   6 m of number 40 constantan at 20°C.
   1 kilometer of number 40 nichrome wire at 500°C.

2. A piece of copper wire has a resistance of 0.84 Ω at 20°C. If it is 10 m long, what gage is it?

3. A tungsten lamp filament has a resistance of 2.63 Ω at 20°C. At what temperature will its resistance be 8.0 Ω?

4. At 20°C a number 26 wire 4.2 m long has a resistance of 0.858 Ω. Of what material is it made?

5. A resistor is heated from 26°C to 88°C; its resistance changes from 138 Ω to 180 Ω. Of what material is it made?

6. Write a paragraph or two on the conclusions that can be drawn from this module regarding the effect of conductor material, length, cross-sectional area and temperature on the resistance of a conductor.

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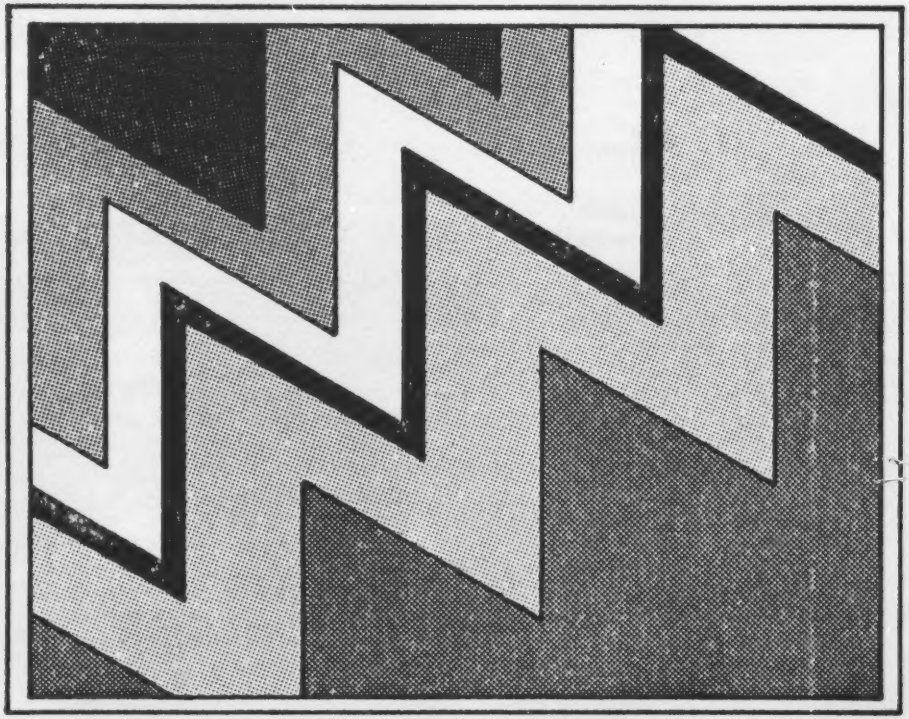
UNIFIED TECHNICAL CONCEPTS

MODULE 5 E 6

RESISTANCE OF SEMICONDUCTOR JUNCTIONS



ELECTRICAL APPLICATION OF RESISTANCE

Technical Education Research Center - Southwest

TERC - SW

INTRODUCTION

Conventional resistors are "fixed" in value (except for temperature changes); therefore, their control of current flow in a circuit also is fixed. Some circuit applications, however, call for a device that has variable control over circuit current, meaning that the resistance of the device must be variable. This module examines the properties of the semiconductor P-N junction diode that make it useful as a voltage-variable resistor. The NPN transistor is analyzed also to demonstrate how resistance of the output circuit is varied, or controlled, by input bias voltage. In the laboratory, the student will measure the resistances of several diodes and transistors.

PREREQUISITES

Student should have completed Concept Module 5-C, "Resistance," and Application Module 5E1, "Ohm's Law."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Define:

  Intrinsic material.
  Extrinsic material.
  Doping.
  P-type material.
  N-type material.
  Depletion region.
  Barrier potential.
  Forward bias.
  Reverse bias.
  Knee voltage.
  Junction resistance.
  Bulk resistance.
  Zener point.

- Explain with the use of a diagram how an NPN transistor is constructed and connected to bias batteries.

- Explain with the use of diagrams how a diode conducts current in one direction but not in the other.

- Explain how changing the current in the emitter-base circuit of an NPN transistor changes the resistance of the base-collector circuit.
- Given the appropriate equipment, measure the resistances of diodes and transistors in a variety of conditions.

DISCUSSION

The current through most materials is inversely proportional to their resistance when an external voltage is applied. The ease with which current flows depends upon availability of the electrons which are to move through the material. In pure (intrinsic) germanium or silicon, electrons are locked into place in each atom in such a manner that conduction cannot occur.

Normally, each carbon, silicon and germanium atom has four electrons in its outer orbit and available for current flow; but in carbon atoms, some of the electrons are not tightly bound but are free to shift from atom to atom. Carbon, therefore, is a better conductor because its valence electrons are more easily moved. As ambient temperature increases, however, some of the electrons in silicon or germanium are energized by heat and consequently break away from their atoms in the crystalline structure, thus becoming more easily available for current flow. The resistance of silicon or germanium, therefore, is lowered as temperature increases and these materials function like conductors. These materials are classified as "semi-conductors," because at low temperatures they are insulators (high resistance), and at higher temperatures conductors (low resistance).

Intrinsic germanium or silicon can have its natural resistance altered by the addition of "impurities" in a process called "doping." Doped germanium or silicon is then called "extrinsic." As mentioned before, germanium or silicon atoms normally have 4 electrons in their outer orbit. These atoms are locked to neighboring atoms in the crystalline structure of the material. Elements such as phosphorous, arsenic and antimony have 5 electrons in their outer orbit. If germanium or silicon is "doped" with any of these three "impurities," then, proportional to the amount of doping, the impurity atoms replace some of the germanium or silicon atoms. At each place in the crystalline structure where this process happens, four of the five electrons of the impurity atom lock into the crystalline structure, and, as before, leave the fifth electron available for conduction, as shown in Figure 1. The heavier the doping, the greater the number of "fifth" electrons available for current flow, and the lower the resistance of the "extrinsic" material. This new, doped, extrinsic material is called "N-type" because electrons (negative) are available as the main, or majority, carrier of current.

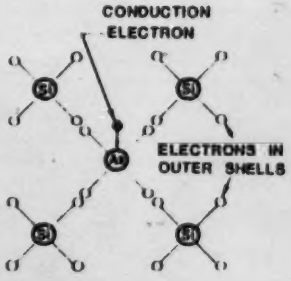


FIG. 1

Boron, aluminum and gallium are examples of elements that have 3 electrons in their outer orbit. When these elements are used to dope germanium or silicon, a "hole" is created where each impurity atom locks into the crystalline structure. The crystalline structure can accomodate four electrons per atom, but only three are present. The space at which the fourth electron is missing is called a "hole," as shown in Figure 2. A hole has the property of a positive charge (absence of

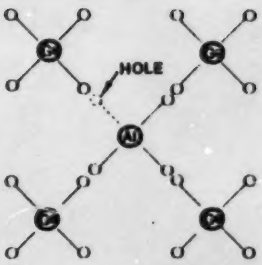
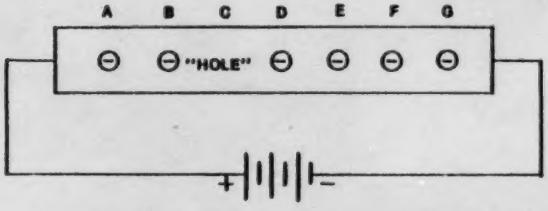


FIG. 2

a negative charge); and it can move or flow in the same manner as an electron moves, although holes flow in the opposite direction from electrons because of their positive charge.

The idea that a hole (being "nothing") can move may seem mystifying at first, but it is a simple concept. In Figure 3, a piece of P-type material doped with impurity atoms to produce "holes" is connected to an external battery to produce current flow. The electrons, being negative charges, are attracted to the positive terminal of the battery, and will move to the left. The holes, being positive charges, should move to the right. Electron D moves to the left and replaces the hole at C. The hole, therefore, is not to the right, at the previous location of electron D. Next, electron E fills the hole at D, and the hole has "moved" another position to the right, to E. As electrons move to the left, holes move to the right. Holes can be represented as stepping stones that allow electrons to travel more easily the distance across the material.



"HOLE" FLOW IN P-TYPE MATERIAL

FIG. 3

P-type and N-type materials, by themselves, are nothing spectacular. They are merely conductors whose resistance is controlled by the amount of doping. In N-type material, electrons are the majority carrier (of current); whereas, in P-type material, holes are the majority carrier. The combination of these two materials in a special way results in a device with properties of voltage-controlled resistance.

When N-type material is joined to P-type material, a junction is formed, as shown in Figure 4a. Immediately, the holes at one side of the junction combine with the electrons at the other side. Where this happens, the majority carriers have been "depleted," and a "barrier potential" is created. The P-type material has become slightly negative because it has lost some positive charge, and the N-type material has become slightly positive because it has lost some electrons, as shown in Figure 4b and c. Recombination may continue as more holes recombine with electrons, but the barrier potential created by the first level of recombination slows down the process. The depletion region widens as recombination continues. Finally, the depletion region becomes so large, and the opposing barrier potential

becomes so great, that holes from the P-type material no longer can cross over the depletion region to recombine with the electrons from the N-type material. Recombination then ceases.

The device so formed is called a P-N junction diode. The barrier potential created in a germanium diode is about 0.3 volts; whereas, the barrier potential for a silicon diode is about 0.7 volts. The resistance of the P and N materials themselves is a function of the percentage of doping, and is generally very low (a few ohms). But the resistance of the depletion region, because there are no majority carriers, is very high, and is inversely proportional to the width of the depletion region. Because the width of this region, and hence the resistance of the diode, can be controlled by an external, or "bias," d.c. voltage, the diode is called a "voltage-controlled" resistor.

When a d.c. voltage is applied in the forward direction (plus to P, minus to N), the holes and electrons, respectively, are pushed by the battery voltage toward the depletion region - electrons toward electrons and holes toward holes, as shown in Figure 5a. Since like charges repel, this process shrinks the depletion region, thus lowering the resistance of the diode. When the applied voltage exceeds the 0.3 volts for germanium or 0.7 volts for silicon, the barrier potential is overcome completely; and the depletion region disappears. The resistance of the diode at this point and beyond is very low

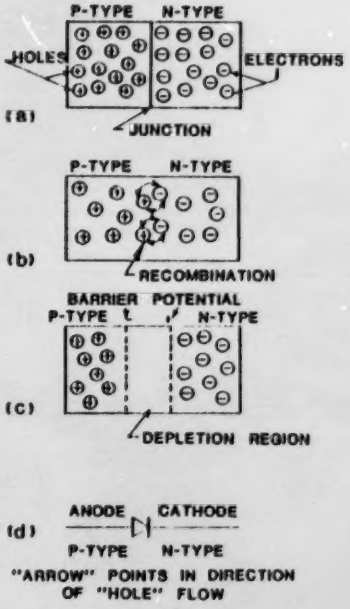


FIG. 4

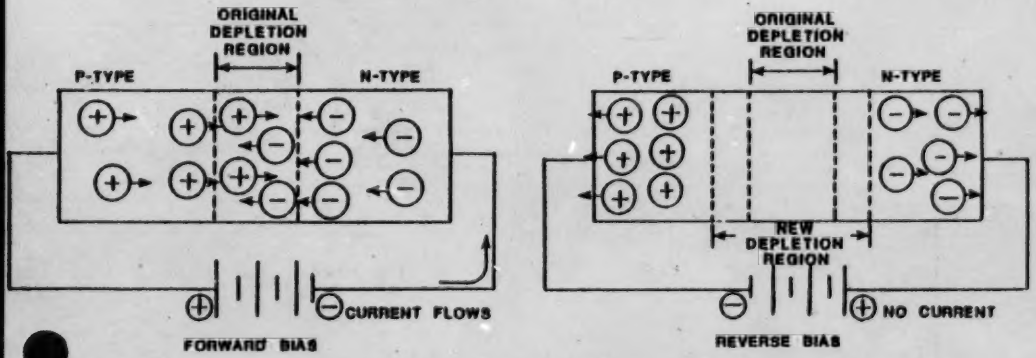


FIG. 5

(a few ohms), and the diode behaves like a short circuit or a closed switch.

In Figure 5b, a reverse-bias voltage will cause holes and electrons to be attracted toward the battery terminals, thus widening the depletion region and causing the diode to exhibit an even larger resistance than in its normal state. Under this condition, the diode exhibits very high resistance and behaves like an open circuit or like an open switch.

Figure 6 shows the current-voltage relationship of a P-N junction diode for various amounts of forward and reverse bias. Resistance at any point on the curve can be found simply by dividing the voltage by the current. As forward bias is applied, starting from zero volts, the depletion region is still large and the diode resistance therefore high. Diode resistance at this point is predominantly the junction resistance, or the resistance of the depletion region. As the forward-bias voltage is increased toward the barrier potential (known as the "knee voltage"), the junction resistance decreases because the depletion region narrows. When the knee voltage is reached, the depletion region disappears; and the curve takes a sharp turn upward, indicating low resistance. Ideally, the diode is considered to have a resistance of 0 ohms when operated beyond its barrier potential, or to appear to be a short circuit (indicated by the vertical dotted line above the knee voltage). But practically all P or N material has some resistance, called bulk resistance, of a few ohms, shown by the sloped line labeled "bulk resistance." Any device has a power limitation (such as a 1/4 watt resistor); diodes are no exception. If too much forward current is forced through the diode, the I^2R product will exceed the power rating of the diode, and burnout will occur.

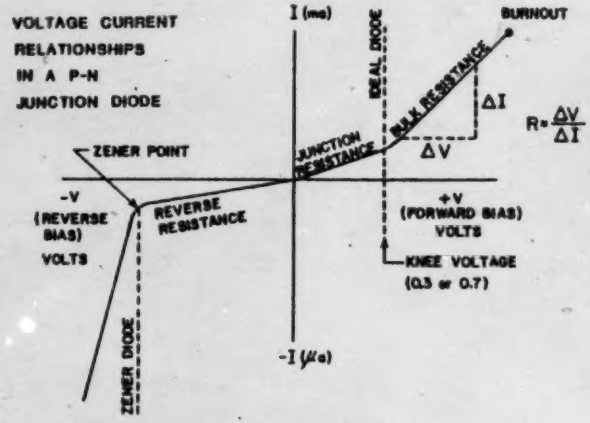
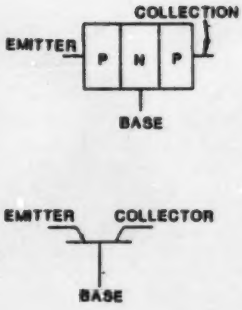


FIG. 6 214

As reverse bias is applied, the diode exhibits some "reverse" resistance, because the widened depletion region has a very high, but measurable, resistance (on the order of megohms). As reverse bias continues to be applied, a point is reached at which breakdown occurs. This is called "zener point," and is the point at which the applied voltage is so great that it forces carriers across the depletion region. This situation is similar to "arc-over" in a switch. With the depletion region broken down, the resistance of the diode drops drastically; and the diode conducts heavily, as the sharp, downward turn of the curve shows. This condition is not necessarily bad, as long as the burnout point is not exceeded. Special diodes, called "zener diodes," are built specifically to operate in this zener region, and are useful as voltage regulators. The dashed line labeled "zener diode" on the curve shows that in this region of operation the current flow through the diode can vary. The voltage across the diode remains constant, making it valuable as a voltage regulator.



TRANSISTORS

The fact that a P-N junction diode is a voltage-controlled resistor whose resistance is a function of the bias voltage applied to it, provides a clue about how a transistor operates. Essentially, a transistor is nothing more than two diodes constructed back-to-back.

Figure 7 shows the two possible variations of transistor construction. Figure 7a shows a P-N junction (emitter-base) connected to an N-P junction (base-collector), with the base (N) being common to both. The reverse is shown in Figure 7b. The terminal with the arrow is called the "emitter"; and the arrow points in the direction of conventional current flow (hole flow), which is the opposite direction of electron flow. In normal operation of the transistor, when properly biased, majority carriers (either holes for PNP type or electrons for NPN type) are "emitted" by the emitter and "collected" by the collector. The amount of this current flow is regulated by the voltage-controlled resistance properties of the transistor.

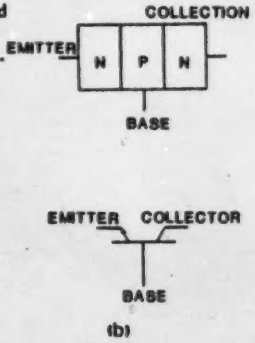


FIG. 7

The biasing of a transistor is important to its proper operation. Figure 8 illustrates how an NPN transistor is connected to a battery supply for correct operation. The emitter-base junction is always forward-biased; therefore, an NPN transistor will have its emitter connected to the minus terminal of the battery, and the base connected to the plus terminal. The resistance of the corresponding diode is low, and current flows very easily in the emitter-base circuit loop. The base-collector junction is always reverse-biased; and, as shown in Figure 8, the collector, which is N-type material, is connected to the plus terminal of a battery, and the base is connected to the minus terminal.

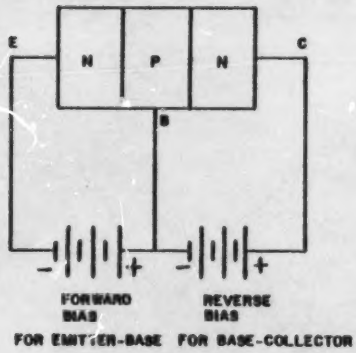


FIG. 8

The resistance of this base-collector loop is thus very high and, theoretically, no current flows in this loop. There is, however, one important requirement in transistor construction which makes the transistor work. This same requirement explains why transistor action cannot be achieved merely by placing two diodes back-to-back: In transistor construction, the base region is of very thin construction. The depletion regions of each diode practically touch each other. Under these conditions, the following happens: Majority carriers (in the case of the NPN transistor, this would be electrons injected by the forward-bias battery into the emitter) flow from the emitter to the base very easily, because of the low resistance to the forward-biased loop. When these majority carriers enter the base region, they "punch through" the base and end up in the collector region, where they are attracted by the plus voltage on the collector terminal. The percentage of electrons traveling through the base to the collector (punching through) is very large - about 90 to 99 percent.

The significance of this punch-through action is this: Normally the resistance of the base-collector junction is very high, and no current would flow in this circuit. But because of the punch-through, the resistance of the base-collector junction is altered, and current flow in the collector circuit is inversely proportional to the altered resistance. In effect, the resistance of the collector (output) circuit is being controlled by the resistance of the emitter (input) circuit. The resistance of the input circuit is transferred to the output circuit; hence, the origin of the name "tran-sistor" (meaning "TRANsfer-reSISTOR").

SUMMARY

Many diodes and transistors have the capacity to vary their resistance to current flow. Such variable resistance is a vital part of some circuits. The small size, great reliability and low cost of these modern devices have been responsible for great strides in electronics.

DIODE RESISTANCE

MATERIALS

1000 ohm resistor, 1/4 watt (current limiter).
IN270 Germanium Diode.
IN914 Silicon Diode.
IN758A Zener Diode.
0-20 volt d.c. power supply.
d.c. milliammeter.
d.c. micro-amp meter.
d.c. voltmeter.
Graph paper.

PROCEDURE

1. Connect circuit as shown in Figure 9.

2. Starting with 0 volts, change voltage in 0.1-volt steps, and record current in Data Table 1. Do not exceed 10 mA.

3. Reverse diode and repeat, except vary voltage in 1-volt steps; record results. Do not exceed 20 volts or 10 mA, whichever comes first. (Remember that current flow before zener point is reached will be in the order of micro-amps.)

4. Repeat 1-3 with the other two diodes, recording results.

5. Plot your results on graph paper labeled "volts" on the horizontal axis and "current" on the vertical axis. The graph should look like Figure 6. The germanium diode will have gradually-changing slopes. Knee-voltage may not be immediately recognized, and there may not be a definite "zener" point. The silicon diode should have a

FIG 9

noticeable knee-voltage at about 0.4 to 0.7 volts, and a noticeable zener point. The zener diode should have the same shape as the silicon diode in the forward region, but have a dramatic zener point at 9.6 volts reverse bias.

6. Calculate resistance of each diode at various points on the curve, using the formula $R = \frac{V}{I}$. Record in Data Table 2. Calculate resistance at the following points:

   a. Midpoint of junction resistance region.
   b. Knee-voltage.
   c. Midpoint of bulk resistance region.
   d. Midpoint of reverse resistance region.
   e. A point past the zener point.

7. How does the resistance of the three diodes differ?

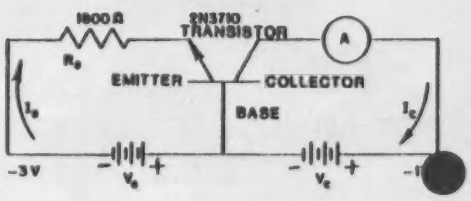
TRANSISTOR RESISTANCE

MATERIALS

2N3710 silicon NPN transistor.
0-20 volt d.c. dual power supply.
d.c. milliammeter.
1800 ohm resistor.
3900 ohm resistor.
6800 ohm resistor.
VTVM.
Graph paper.

PROCEDURE

1. Connect circuit as shown.



2. Calculate I_e (emitter current) from $I = \frac{V_e}{R_e}$. Record in Data Table 3.

3. Measure I_c (collector current); and compare with I_e; and record.

4. Calculate and record resistance of output

circuit from $R_c = \frac{V_c}{I_c}$.

5. Repeat 1-4 with R_e of 3900 ohms and then 6800 ohms. Record.

6. With output voltage set at 17 volts and R_e of 1800 ohms, vary input voltage from 1 to 5 volts in 0.5-volt steps; and record output current in Data Table 4.

7. Calculate and record output resistance R_c for each data point, and draw a graph of output resistance vs. input voltage.

8. What are the basic differences between transistor resistance and diode resistance?

DATA TABLE 1: DIODE RESISTANCE

Germanium Diode		Silicon Diode		Zener Diode	
Voltage (V)	Current (ma)	Voltage (v)	Current (ma)	Voltage (v)	Current (ma)

DATA TABLE 2: CALCULATED DIODE RESISTANCE			
Resistance (Ω) of	Germanium	Silicon	Zener
a. Junction resistance region			
b. Knee voltage			
c. Bulk resistance region			
d. Reverse resistance region			
e. Past zener point			

DATA TABLE 3: TRANSISTOR RESISTANCE					
R_e (Ω)	V_e (V)	I_e (ma)	V_c (V)	I_c (ma)	R_c (Ω)
1800					
3900					
6800					

DATA TABLE 4: CALCULATED TRANSISTOR OUTPUT RESISTANCE				
Steps (0.5 volts)	V_e (V)	I_c (ma)	V_c (V)	R_c (Ω)

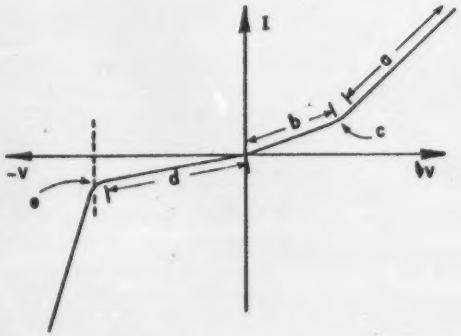
SELF CHECK

1. Define the following terms:

   a. Intrinsic material.
   b. P-type material.
   c. N-type material.
   d. Depletion region.

2. On the curve at the right identify the following:

   a. _____
   b. _____
   c. _____
   d. _____
   e. _____



3. Draw and label a diagram showing the parts of an NPN transistor and the proper connections for bias batteries.

4. Draw diagrams showing the movement of electrons and holes in a diode for:

   a. Forward bias.
   b. Reverse bias.

5. Explain how the resistance of the base-collector circuit of an NPN transistor is controlled by current in the emitter-base circuit.

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Faber, Rodney B. Applied Electricity and Electronics for Technology. New York: John Wiley and Sons, 1978.

Klaylon, Marvin H. Fundamental Electrical Technology. Reading, MA: Addison-Wesley Publishing Company, 1977.

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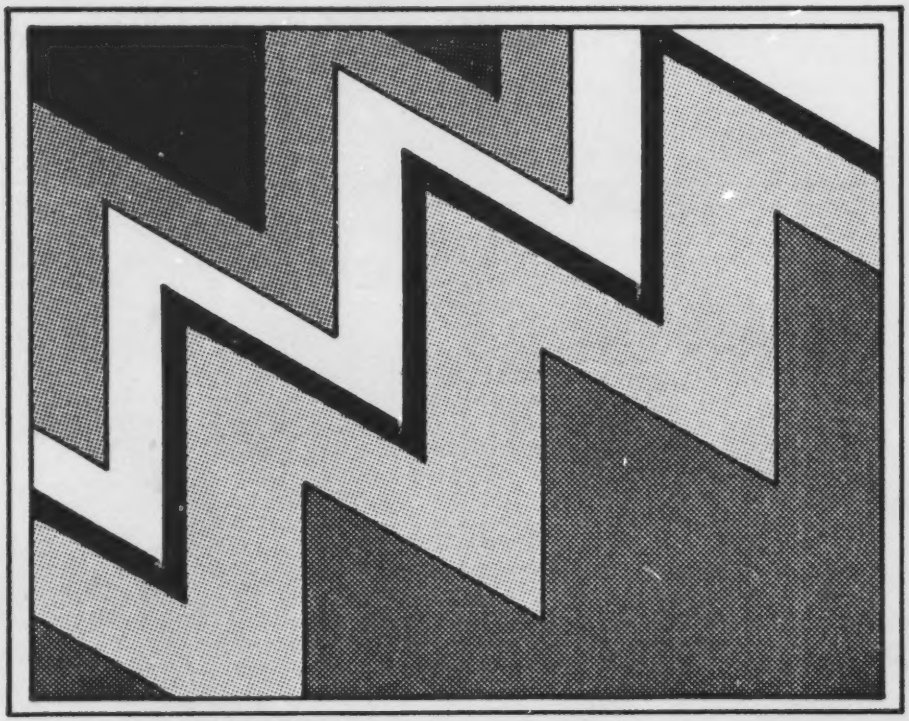
UNIFIED TECHNICAL CONCEPTS

MODULE 5 E 8

VOLT-OHM MILLIAMMETER



ELECTRICAL APPLICATION OF RESISTANCE

Technical Education Research Center - Southwest

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222

INTRODUCTION

Module 5-0, "Resistance," discusses the relationship of voltage, current, and resistance known as Ohm's Law. A volt-ohm-millammeter (VOM) is a device used to measure all three of these electrical quantities. It is one of the most versatile and commonly-used test instruments in technical fields related to electrical and electronic circuits. It is easy to use, rugged, portable, and inexpensive.

Commercial VOM's are available at prices that range from twenty to several hundred dollars. Besides the quality of the components and workmanship that goes into construction, sensitivity is an important criteria in selecting a VOM. Applications determine the sensitivity needed. A meter with a sensitivity range of 20,000 Ω/V is adequate for measurement on most practical circuits, while very high-resistance circuits require meters with a sensitivity of 50,000 to 100,000 Ω/V. On the other hand, some circuits permit the use of a meter with a sensitivity of 1000 Ω/V. Meter sensitivity is determined largely by construction of the movement used to cause needle deflection.

This module deals with the basic elements of the meter and its measurement of the most common electrical quantities. Proper use and precautions to be taken with the instrument also are discussed.

PREREQUISITES

Student should have completed Concept Module 5-0, "Resistance."

OBJECTIVES

Upon completion of this module, the student should be able to:

- List four electrical quantities measured by a VOM.
- Given an actual application requiring the use of a VOM, determine proper adjustments to the range and function switches (when power load is known or unknown) to measure the following:

Voltage.
Current.
Resistance (including zeroing the scale).

- Use a VOM to determine —

  a.c. or d.c. voltage.
  d.c. current.
  Resistance.

DISCUSSION

There are many brands of volt-ohmmeters (VOM's) having different sizes, shapes, and styles. Most of them measure the same basic electrical quantities, which are —

- d.c. voltage.
- d.c. current.
- a.c. voltage.
- Resistance.

The VOM consists of a meter movement, a voltage source (battery), a rectifier circuit, and a collection of resistors that can be switched into the circuit. The position of the needle of the meter is proportional to the direct current through the coils of the meter movement. The additional circuit components are arranged to make meter current proportional to some other quantity being measured. The basic circuits for each type of measurement are described below.

D.C. VOLTAGE

Figure 1 shows the basic current used for d.c. voltage measurement. The value of the resistor is chosen to allow a current to flow through the meter to produce a full-scale needle deflection when a specific voltage is applied to the input. The voltage calibration scale of the meter is changed when one resistor is switched to another.

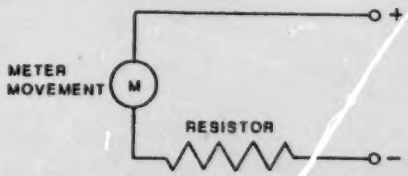


FIG. 1

A.C. VOLTAGE

The circuit used to measure a.c. voltage is the same used for d.c. voltage measurement, except that a rectifier circuit is added. The rectifier changes the a.c. current to a d.c. current to drive the meter movement. Rectifier circuits will be discussed in a later module.

D.C. CURRENT

Figure 2 shows the basic circuit employed in the measurement of d.c. current. The value of the resistor, called a "shunt," is chosen to allow only a small fraction of the current to flow through the meter movement. Most of the current flows through the lower resistance shunt. Current calibration of the meter is changed when one resistor is switched to another.

FIG. 2

RESISTANCE

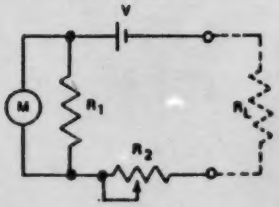


FIG. 3

Figure 3 shows the basic circuit used for resistance measurement in a VOM. The meter responds to a current produced by a battery in the VOM. This current passes through the resistance being measured R_L, and part of it flows through the meter movement to produce needle deflection. Any change in the value of R_1 changes the resistance scale of the meter. R_2 is a variable resistor used to zero the meter.

METER FACE

The front portion or face of the meter includes a function switch and a range switch (Figure 4). The function switch selects the variable to be measured, and is commonly a round know with a pointer that indicates the selection of measurement to be made. It should point to a.c. for a.c. voltage measurement and +d.c. or -d.c. for d.c. voltage, current and resistance measurements. The range switch is used to select the full-scale value that can be measured in current, voltage, or resistance. For example, if the function switch were set to indicate +d.c. and the range switch were set for 250 V, the pointer would show full-scale deflection when a 250 V d.c. source is connected to the test leads of the VOM. The best way to become familiar with a VOM is to use the instrument to perform the measurements described in the laboratory.

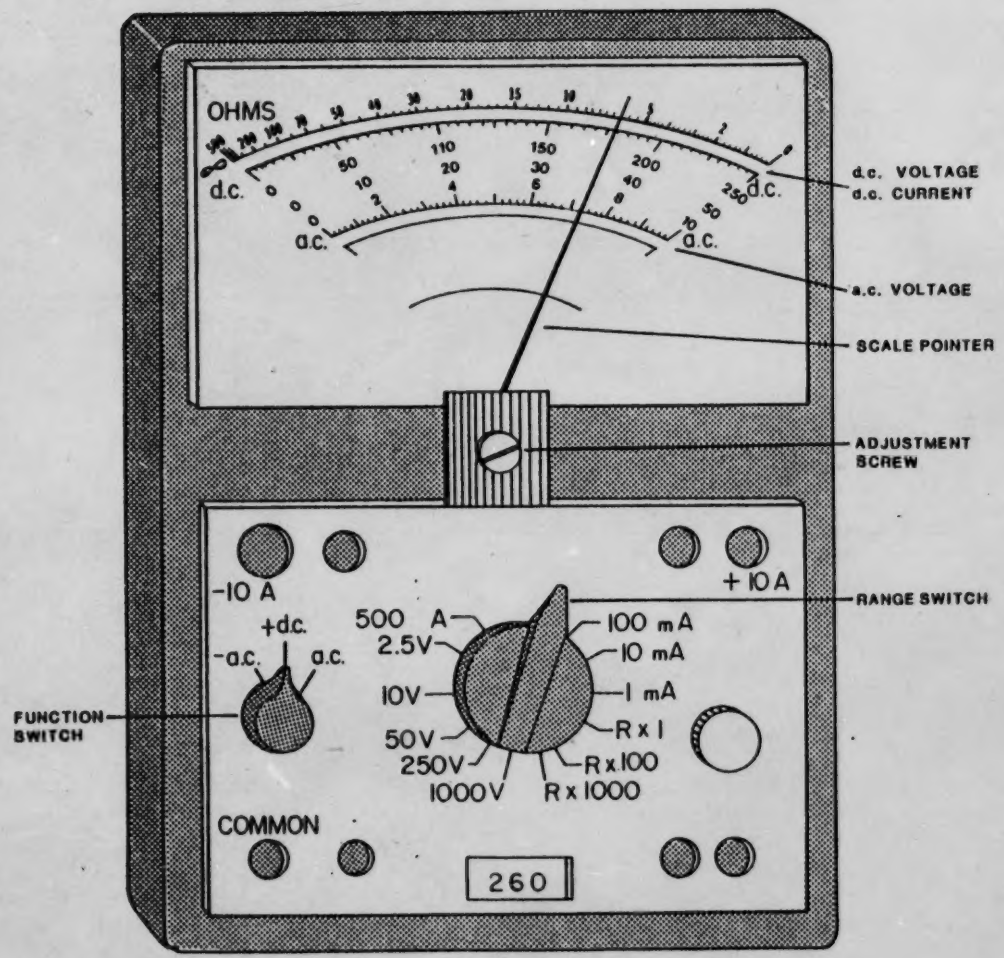

OHMS
d.c.
a.c.
d.c. VOLTAGE
d.c. CURRENT
a.c. VOLTAGE
SCALE POINTER
ADJUSTMENT SCREW
-10 A
+ 10A
RANGE SWITCH
+d.c.
-a.c.
a.c.
FUNCTION SWITCH
500 A
2.5V
10V
50V
250V
1000V
100 mA
10 mA
1 mA
R x 1
R x 100
R x 1000
COMMON
260

FIG. 4

MEASUREMENTS WITH A VOLT-OHM MILLIAMETER

MATERIALS

a.c./d.c. power supply, preferably with a variable output from 0 to 10 volts d.c. and 0 to 12 volts a.c.
Four resistors (one 100 Ω, one 50 Ω and two 25 Ω).
Two test leads from the power supply, preferably one coded red and one black.
A VOM capable of measuring the four electric variables discussed (Simpson type 260 or equivalent).

PROCEDURE

The remainder of this module is a self-paced student exercise in the proper methods for making voltage, current, and resistance measurements with a VOM.

TEST CIRCUIT CONSTRUCTION

Make sure all items in the materials list (or acceptable substitutes) are available. Carefully follow these steps:

1. Make sure power supply switch is off.

2. Connect the resistors (listed in the materials section) in series to create a circuit (Figure 5).

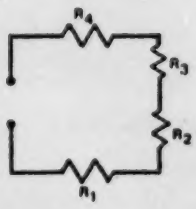


FIG. 5

3. Attach positive lead (usually red) from power supply (Figure 6) to the end of test circuit nearest R_1.

4. Attach negative lead (usually black) from power supply to end of test circuit nearest R_4. Use test circuit (attached to power supply) to check basic VOM functions described below.

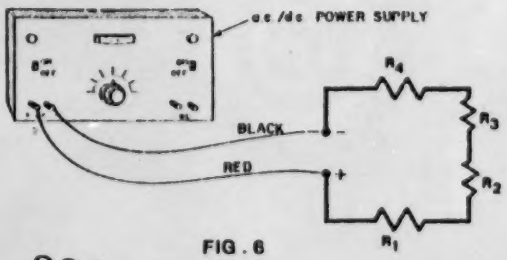


FIG. 6

PROPER USE OF A VOM

Precautions taken to avoid excessive error of measurement and to prevent meter damage can be categorized in accordance with variables being measured.

VOLTAGE MEASUREMENT PRECAUTIONS

When approximate voltage is not known, set range switch to highest setting available. This higher range prevents overranging (damage caused by more energy being sent through the meter than that circuit is capable of recording). After this reading is made, select a lower setting if needed for a more accurate reading.

1. The scale selected should allow readings to be taken from the upper 50% of the scale, when possible, to ensure the most accurate reading.

2. If meter reading changes significantly when switched from one range to another, one probable cause is meter loading. Use a more sensitive VOM if this occurs. Also, some meters need to be rezeroed on each scale before giving consistent readings.

3. To measure voltage, the function switch must be set on voltage — not on current or resistance.

DIRECT CURRENT (D.C.) VOLTAGE MEASUREMENT

Use previously constructed test circuit (Figure 6) and follow these steps:

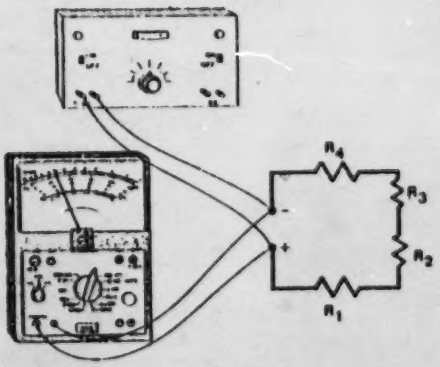


FIG. 7

1. Make sure power supply switch is "off."

2. Set VOM function switch to +d.c.; set range switch to highest voltage scale value (1000 V for VOM shown in Figure 4).

3. Connect positive lead from VOM (Figure 7) to test circuit at the point closest in test circuit to the positive source (from power supply).

4. Connect negative lead to test circuit at the point in test circuit nearest negative source (from power supply).

5. Stop. Request a circuit check from instructor before proceeding.

6. Turn on power supply.

7. The voltmeter reading should be essentially zero at this high range scale.

8. Switch to a lower voltage range scale; the needle should move toward center of scale.

9. Find lowest scale usable without overranging meter; read the meter.

10. Record in Data Table the reading from voltage scale that corresponds to selected value of range switch. Example: reading shown in Figure 8 indicates 6.8 volts, 34 volts or 170 volts on d.c. voltage scales, depending on which voltage scale was selected by range switch.

11. Turn power supply off.

12. Disconnect power supply (only) from circuit.

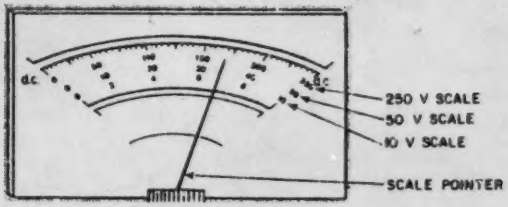


FIG. 8

ALTERNATING CURRENT (A.C.) VOLTAGE MEASUREMENT

1. Make sure power supply switch for a.c. and d.c. is turned off.

2. Connect test circuit lead wires to a.c. outlet of power supply.

3. Set VOM function switch to a.c.

4. Set range switch to highest voltage range.

5. Stop. Request a test circuit check before turning power supply on.

6. Turn power supply on.

7. Reduce range switch setting until scale pointer deflection is in upper half of meter range.

8. Take reading from voltage scale that corresponds to selected value (of range switch); record reading here: _____.

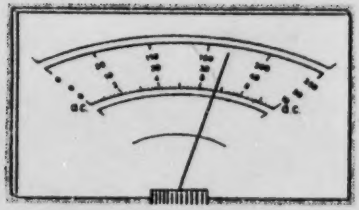


FIG. 9

Example reading (Figure 9) indicates 6.8, 34 or 170 volts a.c., depending on voltage scale selected by range switch.

9. Turn power supply off.

10. Disconnect power supply from circuit.

CURRENT MEASUREMENT PRECAUTIONS

1. Always select a range high enough to prevent meter from overranging.

2. Connect VOM leads in such a manner that meter is in series with circuit under test.

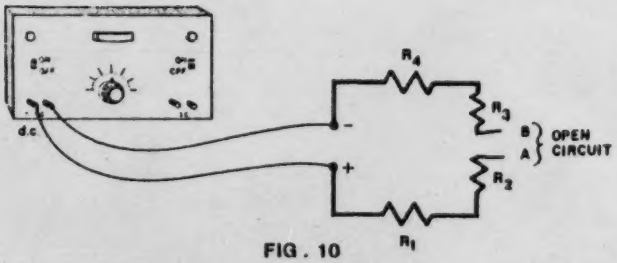


FIG. 10

DIRECT CURRENT (D.C.) MEASUREMENT

1. Make sure that main switch of power supply is turned off. Connect power supply leads to test circuit.

2. Use circuit previously created; interrupt or break circuit as shown in Figure 10.

3. VOM function switch should point to +d.c.

4. Set range switch to highest current range scale available [500 mA (milliampere) for VOM shown in Figure 4].

5. Connect positive lead from VOM to point A (Figure 10).

6. Connect negative lead to point B.

7. Turn on power supply. Note: If scale pointer moves off scale, polarity (positive, +, and negative, -) is reversed and may be corrected by turning function switch from +d.c. to -d.c. or vice versa.

8. Reduce scale value with range switch until reading can be made in upper half of scale without overranging meter.

9. Reading should be made from d.c. scale by using 0-10 values on that scale. Example reading shown in Figure 11 indicates a d.c. current reading of 9 with function switch at 10 mA.

10. Record reading here: _____.

11. Turn power supply off; disconnect VOM; and rejoin break in circuit.

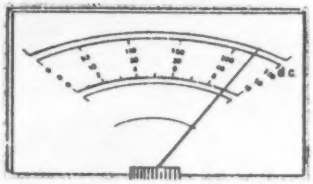


FIG. 11

RESISTANCE MEASUREMENT PRECAUTIONS

1. Make sure power supply is removed from circuit.

2. To ensure accurate measurement, disconnect (from circuit) one end of component to be measured.

3. Each time a new resistance scale is selected, "zero" meter. The meter is "zeroed" by touching together the positive and negative leads and simultaneously turning "zero ohms" selector (Figure 4) until indicator reads zero.

RESISTANCE MEASUREMENT

1. Check each component in test circuit for its resistance value.

2. Set VOM function switch to either +d.c. or -d.c. (polarity is within meter, not circuit).

3. Set range switch to R x 100.

4. Zero meter by touching leads and turning "zero ohms" knob (Figure 4) until meter reads zero ohms on top scale. Note: Needle deflection is opposite for resistance since the zero end of scale is at far right of meter.

5. Disconnect one end of resistor R_1.

6. Attach VOM leads to each side of resistor under test, and read resistance from top scale. Figure 12 indicates a 100 Ω resistance when range switch is set at R x 100.

7. Change range switch to R x 1, and read again; record both readings here: R x 100 = _____ and R x 1 = _____.

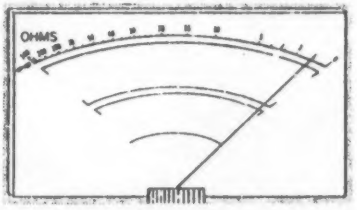


FIG. 12

8. Repeat these steps for each of other three resistors.

9. Record your readings in Data Table.

10. Reconnect all resistors in series.

11. Measure resistance of entire circuit as in Figure 13. Record reading here: _____.

12. Compare this reading with totals from the Data Table.

13. If more than a 25% difference is observed, check with instructor.

14. Disassemble circuit and return all equipment.

15. Describe how a VOM can be used in troubleshooting a circuit.

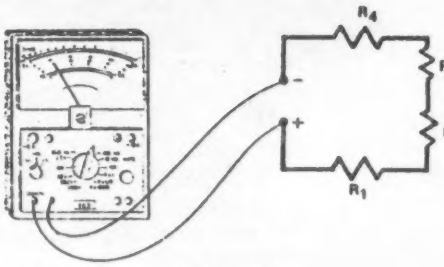


FIG. 13

DATA TABLE				
		Range Switch Scale		
		R x 1	R x 100	
Resistor	R_1			
	R_2			
	R_3			
	R_4			
				= Total Resistance

SELF CHECK

1. Check functions commonly measured by a VOM.

   _____ d.c. voltage.

   _____ a.c. voltage.

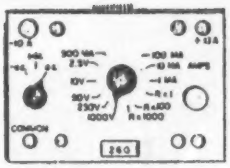
   _____ watts.

   _____ d.c. current.

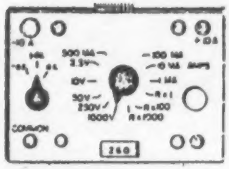
   _____ a.c. current.

   _____ resistance.

2. Circle the meter that illustrates proper settings to be used to measure an approximate 500 V a.c. source.



A.



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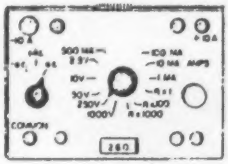

C.

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UTC

UNIFIED TECHNICAL CONCEPTS

MODULE 5 T 1

THERMAL CONDUCTIVITY

THERMAL APPLICATION OF RESISTANCE

Technical Education Research Center - Southwest

TERC - SW

INTRODUCTION

The ability of various materials to conduct heat varies considerably. Materials that conduct heat are called "conductors" or "heat conductors." The best heat conductors are metals. The poorer conductors, such as wood, asbestos, etc., are called insulators. The ability of a substance to transmit heat by conduction is a physical property of the particular material and is characterized by its "thermal conductivity." In this module, we shall investigate heat flow rate of several materials and examine how heat flow rate varies with material, thermal conductivity, and material thickness.

PREREQUISITES

Student should have completed Concept Module 5-0, "Resistance," and have the ability to use a thermometer in measuring temperature (either Fahrenheit or Celsius scale).

OBJECTIVES

To complete this module, the student should be able to:

- Define:
  - Heat conductor.
  - Insulation.
  - Thermal conductivity.
  - Temperature gradient.
  - Heat flow rate.
- Explain how heat flow rate depends on the thermal conductivity, temperature gradient and geometry of a substance.
- Calculate typical heat flow rate problems, given formulae, materials and properties.
- Demonstrate how heat flow rate varies with thermal conductivity and material thickness.
- Given a list of thermal conductivities for various materials, identify good heat conductors and good heat insulators.

DISCUSSION

A metal surface feels cooler than a wooden surface even though they are both at room temperature. This effect is caused by the higher thermal conductivity of the metal. Heat from the hand is conducted away by the metal much more quickly than by the wood. All materials possess varying abilities to conduct heat. The heat transferred through a material can be calculated with the following equation:

$$H = \frac{k\,A\,(T_2 - T_1)}{x} \qquad (1)$$

where

H = heat flow rate (Btu/h) or (cal/s).
k = thermal conductivity (Btu x in/h x ft^2 F°) or (cal x cm/s x cm^2 C°).
A = area (ft^2) or (cm^2).
x = thickness (in) or (cm).
$(T_2 - T_1)$ = difference in temperature between the two surfaces "x" inches apart (F°) or (C°).
$(T_2 - T_1)/x$ = temperature gradient in F°/inch or C°/cm.

The terms used here are shown in Figure 1.

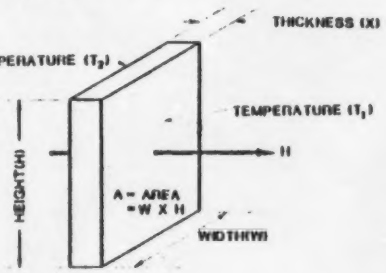


Fig. 1

From Equation 1, the rate of heat flow through a particular material depends on several factors. When the area A is doubled, the flow rate also doubles. Since the thickness x is in the denominator, a doubling of the thickness will cut the flow rate in half. An increase in the temperature difference will also increase the heat flow rate. The remaining term in Equation 1 is the thermal conductivity k. A large value of k gives a high conduction rate. Every material has its own coefficient of thermal conductivity. For example, concrete has a thermal conductivity of:

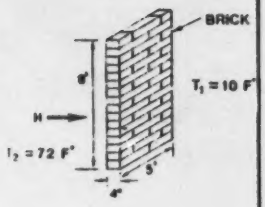
$$\frac{12\ \text{Btu x in}}{\text{h x ft}^2\ \text{F°}}.$$

The thermal conductivities of several common materials are given in Table 1.

TABLE 1. MATERIAL THERMAL CONDUCTIVITIES	
Material	Conductivity (Btu x in/h x ft^2 F°)
Plywood	0.80
Glass fiber insulation	0.25
Concrete	12.0
Brick	9.0

To emphasize this concept further, consider Examples A and B.

EXAMPLE A: HEAT FLOW THROUGH BRICK WALL



Given: An old, broken, 5 ft x 8 ft window is removed and replaced with 4" thick brick. On a particular winter day, the outside temperature is 10° F and the inside temperature is 72° F.

Find: Heat flow through bricked-up opening.

Solution: From Table 1, the thermal conductivity of 4" brick is:

$$k = \frac{9 \text{ Btu x in}}{\text{h x ft}^2 \text{ F°}}$$

$$A = 5 \text{ ft} \times 8 \text{ ft} = 40 \text{ ft}^2$$

$$x = 4 \text{ in}$$

$$(T_2 - T_1) = 72° \text{ F} - 10° \text{ F} = 62 \text{ F°}$$

$$H = \frac{kA\,(T_2 - T_1)}{x}$$

$$= \frac{9 \text{ Btu x } \cancel{\text{in}}}{\text{h x } \cancel{\text{ft}^2}\ \cancel{\text{F°}}} \times \frac{40 \cancel{\text{ft}^2} \times 62 \cancel{\text{F°}}}{4 \cancel{\text{in}}} = 5580 \frac{\text{Btu}}{\text{h}}.$$

From Examples A and B, and Equation 1, materials with higher coefficients of thermal conductivity will have higher heat flow rates if all other parameters are the same. Materials with large values of thermal conductivity have little resistance to heat flow. On the other hand, materials with low thermal conductivities (k ≈ 0.25 Btu x in/h x ft^2 F°) are the most efficient insulators.

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EXAMPLE B: HEAT FLOW THROUGH CONCRETE AND PLYWOOD

Given: All conditions being equal.

Find: Thickness of concrete that will have the same heat flow as 1 square foot of 1 inch plywood.

Solution:

$$H_c = \frac{k_c A (T_2 - T_1)}{x_c} = \frac{12 A (T_2 - T_1)}{x_c}$$

$$H_p = \frac{k_p A (T_2 - T_1)}{x_p} = \frac{0.80 A (T_2 - T_1)}{x_p}$$

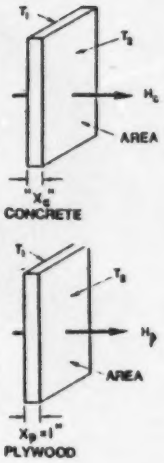
Equating the heat flows:

$$\frac{12 A (T_2 - T_1)}{x_c} = \frac{0.80 A (T_2 - T_1)}{x_p}$$

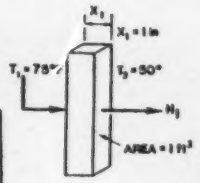
$$x_c = \frac{12}{0.80} \times p$$

$$x_p = 1 \text{ inch}$$

$$x_c = 15 \text{ inches.}$$



Equation 1 indicates that if heat is conducted through two different thicknesses of the same material, the thicker sample would conduct less heat per second. This effect is illustrated in Example C.



EXAMPLE C: HEAT FLOW THROUGH DIFFERENT THICKNESSES OF PLYWOOD

Given: Plywood 1" thick and 12" thick.

Find: Heat flow through each thickness.

Solution:

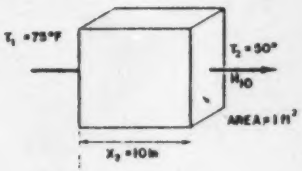
(a) $$H_1 = \frac{k A (T_2 - T_1)}{x_1} = \frac{0.80 \text{ Btu} \times \text{in}}{\text{h} \times \text{ft}^2 \text{ F}^\circ} \times \frac{1 \text{ ft}^2}{1 \text{ in}} \times 25 \text{ F}^\circ$$

$$H_1 = 20.0 \frac{\text{Btu}}{\text{h}}.$$

(b) $$H_{10} = \frac{k A (T_2 - T_1)}{x_2} = \frac{0.80 \text{ Btu} \times \text{in}}{\text{h} \times \text{ft}^2 \text{ F}^\circ} \times \frac{1 \text{ ft}^2}{10 \text{ in}} \times 25 \text{ F}^\circ$$

$$H_{10} = 2 \frac{\text{Btu}}{\text{h}}.$$

Note: The heat flow rate is 10 times less for a sample 10 times thicker.



From these examples, it is shown that the resistance to heat flow can be increased either by choosing a material with a lower thermal conductivity, k, or by increasing the thickness, x, of the material.

EFFECT OF THERMAL CONDUCTIVITY ON HEAT FLOW RATE

MATERIALS

Three heat lamps.
Three oven thermometers.
Container with trays for holding samples.
Three samples of materials with the same area and thickness.
(Wood, concrete, and steel are used in this example, but any three materials with markedly different thermal conductivities will be sufficient.)

PROCEDURE

1. Place three different materials such as wood, concrete and steel in trays A, B and C. The geometry of each tray must be identical.
2. Place an oven thermometer under each of the materials or in appropriately drilled holes near the bottom of each sample as shown in Figure 2. Record the temperature of each thermometer. (Each should read the same room temperature.)
3. Turn on heat lamps and allow a sufficiently long period of heating time to insure that each oven thermometer has reached equilibrium, that is, has reached its highest temperature value.
4. Record temperatures in Data Table 1.
5. From appropriate handbooks, look up conductivities (k) for the materials used and record in Data Table 1.
6. From the recorded data, determine which material permitted the largest and the smallest heat flow rate. Is it true that, other things being equal, the heat flow rate depends directly on the thermal conductivity? What measurement made above was used as an indication of the heat flow rate?

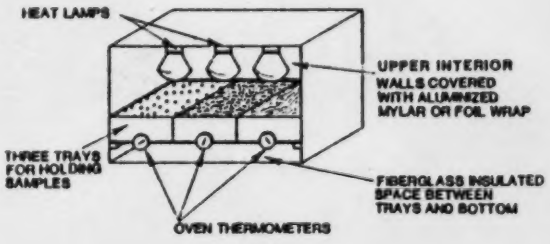

HEAT LAMPS
UPPER INTERIOR WALLS COVERED WITH ALUMINIZED MYLAR OR FOIL WRAP
THREE TRAYS FOR HOLDING SAMPLES
FIBERGLASS INSULATED SPACE BETWEEN TRAYS AND BOTTOM
OVEN THERMOMETERS

Fig. 2

DATA TABLE 1.			
Sample	Material	$k \frac{Btu \times in}{h \times ft^2 F^\circ}$	T (°F)
A	Wood		
B	Concrete		
C	Steel		

EFFECT OF THICKNESS ON HEAT FLOW RATE

MATERIALS

Four oven thermometers.
One piece of aluminum or steel about the size of a "house brick," ~ 2" x 4" x 8".
Ordinary hot plate (110 V).
Sufficient insulation (glass wool or pipe-wrap cork) to cover sides of aluminum "brick" described above.

PROCEDURE

1. Drill holes in aluminum (or steel) brick to just permit insertion of the oven thermometer stems (Figure 3a).
2. Wrap aluminum with appriate insulation so that only top and bottom remain uncovered. Place brick on hot plate, insert oven thermometers, and turn on hot plate. Allow sufficient time for each thermometer to reach equilibrium temperature (Figure 3b).
3. Record temperature of each thermometer and fill in Data Table 2.
4. Plot ΔT versus thickness (ΔX) on a graph

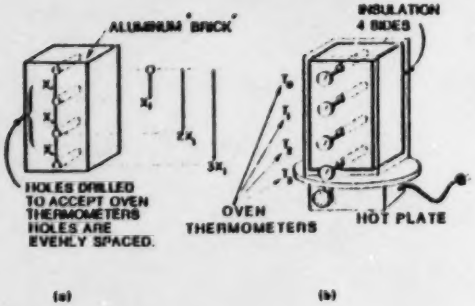


Fig. 3

as shown in Figure 4.

5. What does the graph indicate concerning the heat flow rate as a function of thickness?

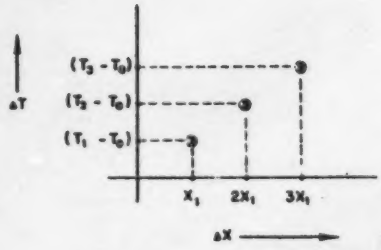


Fig. 4

DATA TABLE 2.				
Thickness	(Top) o	X_1 = __inches	$2X_1$ = __inches	$3X_1$ = __inches
Temperature	T_o = __°F	T_1 = __°F	T_2 = __°F	T_3 = __°F
ΔT		(T_1-T_o) = __F°	(T_2-T_o) = __F°	(T_3-T_o) = __F°

SELF CHECK

1. Define:
   - Heat conductor.
   - Insulation.
   - Thermal conductivity.
   - Temperature gradient.
   - Heat flow rate.
2. The heat flow rate through a plywood wall is 700 Btu per hour. The wall is 8 ft x 12 ft, and the plywood is 3/4"

thick. The temperature on the cool inside surface of the wall is 72° F. What is the outside temperature?

3. What thickness of fiberglass insulation is required for a heat flow rate through one square foot of insulation of 5 Btu/h if the temperature difference is 50 F°?

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UNIFIED TECHNICAL CONCEPTS

MODULE 5 T 2

HEAT FLOW

THROUGH INSULATION

THERMAL APPLICATION OF RESISTANCE

Technical Education Research Center - Southwest

TERC - SW

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INTRODUCTION

As cost of maintaining desired temperatures for businesses and homes increases rapidly, the need for adequate insulation becomes more important. Insulation slows down (impedes, resists) flow of heat in the same manner that a resistor impedes flow of electrical current. Increased insulation can reduce greatly the heat losses in a structure and thereby substantially reduce heating and cooling costs. Previously, the cost of energy has been relatively low, and savings brought about by increased insulation did not offset the added cost. Today, however, increased cost of energy has made better thermal design and added insulation a more realistic investment. In the laboratory, the student will determine the thermal resistance of several commercial insulating materials.

PREREQUISITES

Student should have completed Concept Module 5-0, "Resistance," and Application Module 3T2, "Rate of Heat Conduction."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Define:

  Thermal conductivity.
  Conductance.
  Overall heat transfer coefficient.
  Resistance to heat flow.

- Calculate overall heat transfer coefficient for a system of wall and insulation, given material and resistance data.

- Given the appropriate equipment, measure and record temperature difference across several insulating materials of varying thicknesses; plot data obtained, and explain significance of the curves.

DISCUSSION

The concept of thermal conductivity was discussed in Module 3T2, and will be extended in this module, with emphasis upon commercial insulating materials. The rate of heat flow through a given thickness of material is given by Equation 1.

$$Q_H = \frac{kA\ (T_2 - T_1)}{d} \qquad (1)$$

where

Q_H = heat flow rate, Btu/h or cal/s.

k = coefficient of thermal conductivity, $\frac{\text{Btu} \cdot \text{in}}{\text{h} \cdot \text{ft}^2\ ^\circ\text{F}}$ or $\frac{\text{cal} \cdot \text{cm}}{\text{h} \cdot \text{cm}^2\ ^\circ\text{C}}$.

A = area ft^2 or cm^2.

$(T_2 - T_1)$ = difference in temperature between the two surfaces "d" ft or cm apart.

d = thickness of two surfaces considered, ft or cm.

Materials with high thermal conductivities k permit larger heat flow rates than materials with small values of k. For example, concrete has the following thermal conductivity:

$$k = 12\ \frac{\text{Btu} \cdot \text{in}}{\text{h} \cdot \text{ft}^2\ ^\circ\text{F}}$$

Fiberglass insulation, however, has this thermal conductivity:

$$k = 0.25\ \frac{\text{Btu} \cdot \text{in}}{\text{h} \cdot \text{ft}^2\ ^\circ\text{F}}$$

CONDUCTANCE DEFINED

The term "conductance" is used for heat flow through materials that do not have a uniform or similar structure throughout the considered cross section (inhomogeneous). Conductance is defined as heat flow rate in Btu/hour through one square foot of an inhomogeneous material of a given thickness for a one degree difference in temperature between the two surfaces, or faces, of the material (Figure 1).

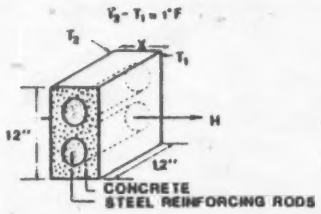


FIG. 1

Heat transfer by conduction through an inhomogeneous material can be calculated, as shown in

Equation 2.

$$Q_H = CA\,(T_2 - T_1) \qquad (2)$$

where

Q_H = heat flow rate, Btu/h or cal/s.

A = area, ft^2 or cm^2.

$(T_2 - T_1)$ = difference in temperature between the two surfaces, °F.

C = conductance, $\frac{Btu}{h \cdot ft^2 \cdot °F}$ or $\frac{cal}{s \cdot cm^2 \cdot °C}$

For a material that has a uniform or similar structure throughout (is homogeneous) with a specific value for thermal conductivity k, the conductance C is given by Equation 3.

$$C = \frac{k}{d} \qquad (3)$$

where

d = thickness between the two surfaces of temperatures T_1 and T_2.

Resistance to heat flow is defined as the reciprocal of the conductance, as in Equation 4.

$$R = \frac{1}{C} \qquad (4)$$

where

R = resistance, $\frac{h \cdot ft^2 \cdot °F}{Btu}$ or $\frac{s \cdot cm^2 \cdot °C}{cal}$.

Example A illustrates the use of Equations 2, 3 and 4.

EXAMPLE A: HEAT FLOW THROUGH A BRICK WALL

Given: Heat flow through a 4-inch brick where k = 9 Btu·in/hr · ft^2 °F and x = 4 inches.

Find: Resistance to heat flow.

Solution: $C = \frac{k}{x} = \frac{9}{4} \frac{Btu \cdot \cancel{in}}{h \cdot ft^2 \cdot °F \cdot \cancel{in}}$

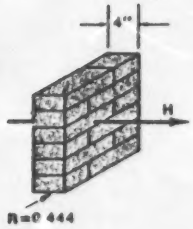
Therefore:

$C = 2.25 \frac{Btu}{h \cdot ft^2 \cdot °F}$

$$k = \frac{9 \text{ Btu} \cdot \text{in}}{\text{h} \cdot \text{ft}^2 \ ^\circ\text{F}}$$

And resistance of the 4-inch brick is:

$$R = \frac{1}{C} = \frac{1}{2.25} = 0.444$$



Note: The units of $\frac{\text{h} \cdot \text{ft}^2 \ ^\circ\text{F}}{\text{Btu}}$ are usually omitted.

If a compound wall is made of several different materials, the heat conducted through the wall is given by Equation 5.

$$Q_H = UA\ (T_2 - T_1) \qquad (5)$$

where

Q_H = heat flow rate, Btu/h or cal/s.

U = overall heat transfer coefficient of wall, $\frac{\text{Btu}}{\text{h} \quad \text{ft}^2 \ ^\circ\text{F}}$ or $\frac{\text{cal}}{\text{s} \quad \text{cm}^2 \ ^\circ\text{C}}$.

A = area, ft^2 or cm^2.

$T_2 - T_1$ = temperature difference between surfaces of the wall, °F or °C.

The overall heat transfer coefficient is simply the overall conductance, and is equal to the reciprocal of the total resistance, as indicated by Equation 6.

$$U = \frac{1}{R_T} \qquad (6)$$

where

R_T = total resistance, as derived by Equation 7.

Equation 7 gives the total resistance, R_T (R-value) of the individual wall components.

$$R_T = R_1 + R_2 + R_3 + \ldots R_n \qquad (7)$$

where

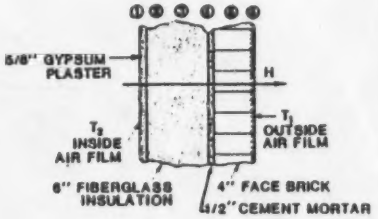
$R_1, R_2, \ldots R_n$ = resistances of individual components in the compound wall.

Total resistance R_T commonly is referred to as the R-value, and is illustrated in Example B.

EXAMPLE B: HEAT CONDUCTED THROUGH AN INSULATED WALL

Given: Resistance data below.

Find: (1) Value of total resistance.
(2) General formulas for overall heat flow rate for the insulated wall illustrated in the figure.



Solution:

Item	Description	Resistance*
1	Inside air film	0.68
2	5/8" gypsum plaster	0.39
3	6" fiberglass insulation	24.00
4	1/2" mortar cement	0.10
5	4" face brick	0.44
6	Outside air film	0.17
	Total resistance = R_T =	25.78

*Values of resistances can be found in various air conditioning and refrigeration manuals and handbooks.

93% of all the resistance comes from the insulation.

(1) Thus, total resistance R_T = 25.78. From this value and Equation 6, calculate overall heat transfer coefficient as follows:

$$U = \frac{1}{R_T} = \frac{1}{25.78} = 0.03879$$

(2) Calculate Q_H, heat flow rate, for the inhomogeneous wall. Thus, with A and $(T_2 - T_1)$ known, the below results:

$$Q_H = 0.03879\ A\ (T_2 - T_1)$$

Since fiberglass is the most common insulation, its R-value is especially important. The thermal conductivity for fiberglass insulation is

$$k = 0.25\ \frac{Btu \cdot in}{h \cdot ft^2\ ^\circ F}$$

therefore, resistance, or R-value, for 3 inches of fiberglass insulation is

$$R = \frac{d}{k} = \frac{3''}{0.25} = 12.$$

Resistance, or R-value, for 6 inches of the same insulation is

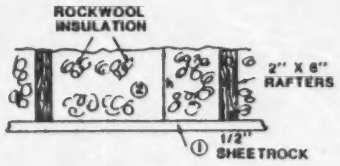
$$R = \frac{d}{k} = \frac{6''}{0.25} = 24.$$

Resistance, or R-value, is very useful in the purchase of insulation or in the specifying of insulation requirements.

EXAMPLE C: HEAT CONDUCTED THROUGH A COMPOUND CEILING

Given: Data below.

Find: Thickness of insulating rockwool required to give an R-value of 39 for the ceiling. (R-values of 39 currently are being advertised to reduce heating and air conditioning bills by at least 50%.)



Solution: 1 1/2" sheetrock where: $k_s = 6 \left(\frac{Btu \cdot in}{h \cdot ft^2 \cdot {}^\circ F}\right)$

2 rockwool insulation where: $k_R = 0.3 \left(\frac{Btu \cdot in}{h \cdot ft^2 \cdot {}^\circ F}\right)$

for 1: $R_s = \frac{1}{C_s} = \frac{d}{k_s} = \frac{1/2"}{6} = 0.0833$

for 2: $R_R = \frac{1}{C_R} = \frac{d}{k_R} = \frac{h}{0.3}$

$R_T = 39 = 0.0833 + h/0.3$

When the above equation is solved for h, the result is this:

$$h = 11.68 \text{ in}$$

R-values of 39 can be reached by increasing standard 6" ceiling insulation to 12".

SUMMARY

The purpose of insulation is to resist the flow of heat. Heat flows at a given rate for various materials. The heat flow rate of an object, such as a wall, can be calculated by adding all the individual resistances that it contains.

COMPARISON OF INSULATING MATERIALS

MATERIALS

Three heat lamps.
Four oven thermometers.
Containers with trays for holding samples.
Three samples of insulation with different R-values, such as the following:

- Fiberglass (3 thicknesses) sheet.
- Polyethylene sheeting.
- Rockwool.
- Fiberglass – loose or blown.
- Polystyrene (as used in home insulation).

PROCEDURE

1. Place three different insulation samples (coded A, B, C) in trays, as shown in Figure 2.
2. Place a thermometer under each material, and one on top of middle sample.
3. Turn on heat lamps; allow system to come to thermal equilibrium (thermometers reach a steady temperature).
4. Record temperatures from each sample in Data Table.
5. Plot data as shown in Figure 3.
6. How does temperature recorded at underside of each sheet of insulation vary with R-value?

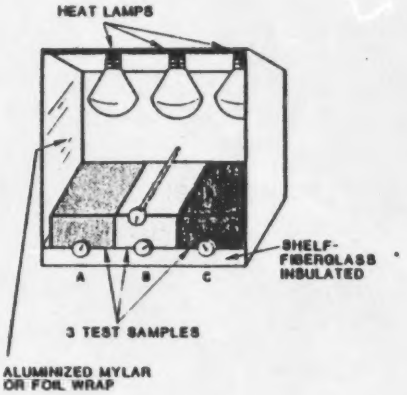


FIG. 2

DATA TABLE			
Sample	Type Insulation	R-Value	T
A			
B			
C			

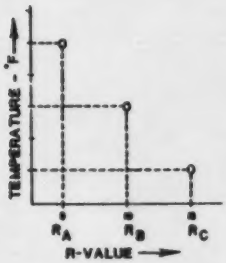


FIG. 3

SELF CHECK

1. Define:

   Thermal conductivity.
   Conductance.
   Resistance to heat flow.

2. Qualitatively describe results of the experiment, and explain results of the data plotted in Figure 3.

3. Using data given, calculate overall heat transfer coefficient, U = 1/R, for the insulated wall illustrated in Figure 4.

Material	Resistance
1	0.68
2	0.39
3	12.00
4	0.10
5	1.0
6	0.17

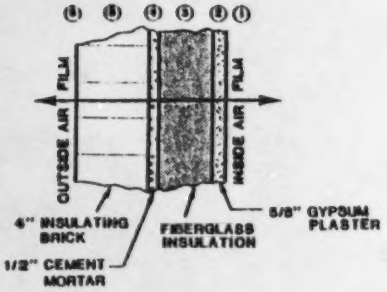


FIG. 4

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